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Research Article

Nasal coarticulation changes over time in Philadelphia English

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ABSTRACT

This study examines change over time in coarticulatory vowel nasality in both real and apparent time in Philadelphia English. We measure nasal-adjacent vowels in words from a corpus of conversational speech and find systematic, community-level changes in degree of nasal coarticulation over time in Philadelphia. Specifically, in all speakers who were under the age of 25 when interviewed, there is an overall trend of increasing nasality in people born between 1950 and 1965, yet people born after 1965 move towards less nasality than speakers born earlier; finally, those born after 1980 reverse this change, moving again toward greater nasal coarticulation. This finding adds nasality to the set of phonetic dimensions that are demonstrably susceptible to diachronic change in a speech community. The observation that the degree of nasal coarticulation changes towards increased coarticulation at one time period and decreased coarticulation at a different time period adds to the growing body of evidence that subphonemic variation is not universally determined, suggesting instead that it is learned and encoded. Furthermore, the changes in nasality are independent from an observed frequency effect. These empirical patterns suggest that language-internal factors, such as lexical frequency, are independent from language external factors, such as community-level phonetic change over time.

1. Introduction

This paper presents a sociophonetic case study of an ongoing change in degree of nasal coarticulation in Philadelphia English. It is by now a familiar empirical observation that American English speech communities systematically vary and gradually change over time in the fine-grained, subphonemic properties of their vowel productions, both in formant centroids (Labov, 1994; Labov, Ash, & Boberg, 2006) and dynamic trajectory targets (Jacewicz, Fox, & Salmons, 2011). Less attention, however, has been directed at how other non-contrastive phonetic features, such as degree of coarticulation, might vary across or be changing within these speech communities. The current study examines fluctuations over time in the degree of nasal coarticulation in the speech of Philadelphians, with nasal coarticulation measured as acoustic nasality in vowels adjacent to a nasal consonant. We investigate the role of both social factors, namely speaker sex, age, and birthyear, and language-internal factors, including lexical frequency and neighborhood density, in these fluctuations.

1.1. Phonetic variation and change

The focus of the current study is a change in progress in the production of nasal coarticulation, a non-contrastive feature in English, in the Philadelphia speech community. Substantial progress has been made in documenting other phonetic-level diachronic changes in the Philadelphia dialect. Labov (2001), based on the apparent-time[1] dimension of fieldwork carried out in the 1970s, reports on 15 different vowel changes at a range of stages of development. Of these, only one (the raising of [aɪ] before voiceless consonants) appears to have led to a true phonemic split (Fruehwald, 2008), while the remainder represent subphonemic changes in the height and/or advancement of the vowel target. Numerous subsequent studies have explored the acquisition, social embedding,

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[1] The apparent-time hypothesis holds that, given the strong tendency towards post-adolescent stability in the linguistic systems of individuals, age differences observed in a speech community at a single point in time can be understood to reflect true diachronic change at the community level (Bailey, Wikle, Tillery, & Sand, 1991).

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and linguistic effects of these changes in great detail (Conn, 2005; Hindle, 1980; Labov, Rosenfelder, & Fruehwald, 2013; Payne, 1976; Roberts, 1997; Wagner, 2008; inter alia). The recent development of the Philadelphia Neighborhood Corpus, which consists of over 1000 interviews recorded between 1972 and 2013 with speakers born between 1888 and 1991, provides an unparalleled depth of both apparent time and real time within which we might reasonably hope to observe other kinds of subphonemic variation. In this study we focus on the identification of a community-level change in coarticulatory degree over time, which appears to be similar to the vowel changes just discussed in that it is gradual and does not appear to lead to phonological reorganization. In Section 4.4 we entertain the possibility that the similarities between these types of changes go even deeper, perhaps reflecting social changes in Philadelphians' self-identification, as suggested by Labov et al. (2013).

Philadelphia is far from being the only speech community in which fine-grained diachronic changes in the subphonemic pronunciation of vowel phonemes have been documented. Numerous other sociophonetic studies have outlined the phonetic variation present in other American English speech communities in their production of vowel formants (for an overview of American English vowel diversity, see Labov et al., 2006). Furthermore, vowel formant values are not the only subphonemic properties that have been shown to be subject to change in a speech community. For example, there is evidence that several Cantonese tone contour patterns are changing slightly among speakers in Hong Kong, though the suggestion is that this might lead to a phoneme merger of several tone pairs (Mok, Zuo, & Wong, 2013). Additionally, numerous studies have documented that the fine-grained details in the pronunciation of phonemes are dialectally, socially or stylistically motivated and used, such as vowel-intrinsic *F*0 (Fox & Jacewicz, 2014), /s/ articulation (Stuart-Smith, 2007), glottalization of /t/ (Docherty & Foulkes, 2005), and consonant strength (Lavoie, 2001). The evidence for the encoding and sociolinguistic selectivity of subphonemic variability raises the possibility that we might find change over time in other non-contrastive properties of speech at the community level. We predict that such a change can also be observed in degree of coarticulation, a non-contrastive dimension of speech, which is discussed in the following section.

We particularly emphasize the differentiation of community-level change over time from change across the lifespan of individuals, both of which are relevant for subphonemic characteristics of speech. The standard approach in the sociolinguistic literature just discussed is to rely heavily on the apparent time hypothesis, with its attendant assumption of post-critical-period stability. However, studies of change across the lifespan of individuals are now beginning to gain traction in sociolinguistics after the accumulation of decades of data (Sankoff & Blondeau, 2007; Wagner & Sankoff, 2011). Some of the lifespan changes that have been attested are subphonemic. For example, the Queen of England's vowel formants have been observed to change over her adult lifespan to be more phonetically similar to the popular Southern British English dialect (Harrington, Palethorpe, & Watson, 2000). Lifespan changes in the production of fine-grained phonetic detail may be driven both by dialect exposure and regional identification—adults who have moved from Canada to New York City are shown to make at least minor modifications to their target for [aʊ] raising before voiceless consonants, gradually converging towards the lower nucleus of the New York target (Nycz, 2011). Numerous studies report change in production targets of vowel production in other English dialects across the lifespan due to factors such as mobility (Foulkes & Docherty, 1999) and education (Evans & Iverson, 2007). One recent study, which documents a real-time change in degree of nasal coarticulation over the lifespan of an individual, compares acoustic nasal coarticulation in vowels from two lectures given by Noam Chomsky in 1970 and 2009 and finds that his vowels are significantly more nasal at the later time (Kwon, 2013).

These studies suggest that subphonemic change within the lifespan of an individual, including change in coarticulatory nasality, is possible, if not inevitable. Although the data in the current study do have real-time depth from being collected across four decades, there is also a high correlation between speaker age at time of interview and speaker birthyear. Any changes we observe in this corpus that correlate jointly with both age and birthyear should thus be carefully examined to distinguish these two phenomena. This study was designed to test the prediction that subphonemic patterns of coarticulation are subject to sociolinguistic change, through time in a speech community and/or over the lifespan of individuals. We aim to disentangle these two possibilities from a corpus of naturalistic speech where diachronic time (birthyear) and lifespan time (age) are highly collinear.

1.2. Coarticulatory variation

The term *coarticulation* refers to the fact that speech often simultaneously exhibits properties of multiple phones due to articulatory overlap, even if the phonological representations of these segments are distinct. Traditionally, coarticulation was viewed as physiologically determined, resulting from the articulatory implementation of adjacent segments (Chomsky & Halle, 1968). Yet, subsequent research indicating that coarticulation patterns both are language-specific and vary systematically within a language implies that coarticulation cannot be purely a mechanical side effect of phoneme production (e.g., Beddor, Harnsberger, & Lindemann, 2002; Manuel, 1990; Manuel & Krakow, 1984). The focus of the present study is nasal coarticulation, the overlapping velum gesture on vowels adjacent to nasal consonants. There are three types of empirical findings to support our focus on nasal coarticulation as a particularly relevant and appropriate variable in the study of socio-phonetic change: cross-linguistic variation, language-internal linguistic variation, and stylistic or contextual variation.

First, it is a consistent finding that languages vary in their degree of nasal coarticulation. Sometimes these language-specific patterns of nasal coarticulation can be traced to perceptual motivations for keeping phonemic and coarticulatory nasalization distinct; for example, the magnitude of nasal coarticulation in French, which has a set of phonemic nasal vowels, is much smaller than in English (Cohn, 1990; Delvaux, Demolin, Harmegnies, & Soquet, 2008). In contrast, Clumeck (1976) found little to no correlation between degree of nasal coarticulation and phonemic status of vowel nasality. This lack of direct correlation continues to be confirmed. The minimal degree of contextual nasal coarticulation in Italian, for example, is comparable to that in French, despite the fact that Italian lacks an oral-nasal phonemic vowel contrast (Farnetani, 1990). Furthermore, other articulatory details about nasalization, besides just magnitude, appear encoded in the language; for example, an aerodynamic comparison of two African languages, Akan and Agwagwune, which differ in the phonemic status of vowel nasalization parallel to English and French, found that the attendant difference in coarticulation is not one of magnitude but rather one of the timing and location of peak nasalization (Huffman, 1988). Such conflicting results in cross-linguistic comparisons suggest that coarticulatory patterns are arbitrary and learned, perhaps arising from numerous diachronic facts about a language rather than solely from a perceptually-driven desire to prevent conflict between phonological and phonetic nasality. This suggestion is further strengthened by van Reenen's (1982) observation that phonemically nasal vowels in European (Parisian) French are more nasalized than nasal vowels in Canadian (Quebecois) French, a difference which cannot be clearly accounted for by differences in the phonological system because the feature-structural value of nasal vowels in both dialects is ostensibly the same (Cohn, 1990). Overall, the available evidence points to inter-language and dialectal nasal coarticulation patterns being at least partially learned.

Second, besides varying across languages and dialects, coarticulation also varies within languages in ways that are systematically sensitive to language-internal factors. For instance, vowel-to-vowel coarticulation varies depending on the type of prosodic boundary a sequence spans: more coarticulatory resistance is found in sequences spanning larger prosodic boundaries than in sequences spanning smaller prosodic boundaries (Cho, 2004). Degree of nasal coarticulation, in particular, is adjusted in response to varying speaking rates such that a constant proportion of temporal overlap between nasal and vowel is maintained in English (Bell-Berti & Krakow, 1991; Solé, 1992), but not in Spanish (Solé, 1995). This suggests that the extent to which consonant nasality is allowed to impinge on the adjacent vowel is a detail that speakers actively maintain in production. Furthermore, coarticulatory nasality is shown to be sensitive to lexical properties, such as phonological neighborhood density: words from highly dense phonological neighborhoods exhibit greater degree of vowel-to-vowel and nasal coarticulation than words from more sparse neighborhoods (Scarborough, 2004, 2013). Increases in coarticulation as a function of increased neighborhood density co-occur with increased hyperarticulation, suggesting that an increased degree of coarticulation serves to make words with many similar sounding competitors more distinct through acoustic enhancement of their phonological components (Scarborough, 2013). Neighborhood density has been reported to influence nasality in lab studies (Scarborough, 2013) but has not been investigated in natural speech corpora. Since the influence of neighborhood density on degree of nasal coarticulation has been previously established, we include this variable as a factor which we expect to likewise condition nasality in the natural speech of Philadelphians.

Finally, degree of coarticulatory nasality varies systematically in contextual ways, suggesting at least that its implementation is under speaker control and at most that speakers use nasal coarticulation patterns to create meaningful structures in the speech signal. Stylistically, increasing nasality was observed to be recruited for use in conveying various stereotypes such as “nerd” and “valley girl” in an experimental setting (Podesva, Hilton, Moon, & Szakay, 2013). Furthermore, degree of nasal coarticulation varies as a function of interlocutor (Scarborough & Zellou, 2013), with speakers increasing their degree of coarticulation in a map task with a real interlocutor but decreasing their degree of coarticulation when conveying information to an imaginary hard-of-hearing interlocutor. Another empirical finding is that the magnitude of nasal coarticulation is subject to phonetic imitation: speakers who are asked to repeat words with varying degrees of coarticulatory vowel nasality co-vary their degree of nasality (Zellou, Scarborough, & Nielsen, 2013). All these findings indicate that degree of nasal coarticulation is under speaker control to the extent that it is sensitive to stylistic and socio-contextual factors.

Extensive empirical support that nasal coarticulation is language-specific, can be sensitive to language-internal structural factors, and is subject to within-speaker variation based on various social and stylistic contexts leads us to expect that it may be subject to socially-motivated change as well. This paper shows that nasal coarticulation is indeed a feature that is susceptible to sociophonetic change.

1.3. Coarticulation and sound change

Previous discussions of the role of coarticulation in sound change in the literature have been primarily concerned with the mechanisms by which coarticulation might lead to phonological change. Specifically, Ohala (1975, 1993) argues that listener misattribution of the acoustic effects of coarticulation to phonological representations leads to reanalysis. For example, /bænd/ might be produced as [bæ̃d], then subsequently misperceived as /bɛd/ due to the remaining spectral effects of nasalization which cannot be attributed to a surface nasal consonant (see, for example, Beddor, 2009; Delattre, 1954; Krakow, Beddor, Goldstein, & Fowler, 1988 for further discussion and supporting evidence). In a similar vein, it has been suggested that nasal coarticulation and vowel-to-vowel coarticulation might be phonologized as phonemic vowel nasality and vowel harmony, respectively (Beddor, Krakow, & Lindemann, 2001). Our approach diverges from the tradition of these types of accounts, which are concerned with how non-contrastive coarticulatory features develop into phonological contrast. Specifically, we aim to apply methods for observing fine-grained changes over time in vowel quality to test whether changes in nasal coarticulation can similarly vary systematically in a speech community. Our current focus is the prediction that the magnitude of the phonetic implementation of coarticulation can vary over time.

There are conflicting views of the role of articulatory demands in influencing coarticulatory variation. One notion is that coarticulatory magnitude is inversely related to articulatory effort (e.g., Lindblom, 1990; Moon & Lindblom, 1994). Under this view, speakers attempt to reduce articulatory effort by increasing speech rate at the expense of reaching full articulatory targets; this would result in greater segmental overlap. In this view, at least implicitly, increased coarticulation is articulatory preferential and the default in the absence of pressure to exert more effort, leading to the prediction that coarticulation should increase over time. An alternative possibility is that increasing the magnitude of individual articulatory gestures could also increase their degree of overlap—a stance that would predict decreasing coarticulation with reductions in articulatory effort and therefore an overall decrease in coarticulation over time. Note that both of these predictions share the assumption that the natural direction of sound change over time is towards decreased articulatory effort (e.g. Bybee, 2002); the difference is whether the decreased effort should lead to greater or lesser coarticulation. Regardless of which view is correct, though, if a purely gestural approach to coarticulatory change were correct, we would expect to see changes in coarticulation predominantly in one direction of coarticulatory degree. Beyond strictly articulatory accounts, a functional factor that might also predict coarticulatory change toward increasing nasality is the recruitment of nasal coarticulation by speakers for the purposes of phoneme enhancement (Kingston & Diehl, 1994). An alternative formulation of essentially the same stance is the proposal that speakers actively control and enhance language-specific production patterns, integrating them into phonetic representations and speech planning such that articulatorily natural effects emerge (Hoole, Kühnert, & Pouplier, 2012). Under this approach, the phonetic system 'exploits' the physiological baselines of the language. If we observe change only in a single direction, then we might appeal to either or both articulatory efficiency and speaker enhancement of language-specified coarticulatory patterns (cf. Hoole et al., 2012). All of these explanations point to a prediction of unidirectional change.

On the other hand, if we observe *bidirectional* change, it would be inconsistent with the deterministic predictions of the above possibilities, suggesting that any explanation relying solely on one of those factors would be too simplistic. However, those views do not take into account social or stylistic motivations that might offset any articulatorily- or perceptually-driven biases in phonetic change. Sociostylistic motivations can introduce a range of possibilities in terms of what we would expect to find in change over time because they must be learned arbitrarily. To the extent that we see non-deterministic changes to nasal coarticulation patterns at the speech community level, it supports the suggestion that subphonemic variation such as coarticulation is subject to recruitment for stylistic purposes or associated with social identities. Of course, this would not rule out the involvement of articulatory or functional constraints; indeed, our view is that multiple factors are likely at work simultaneously.

1.4. Lexical frequency

Lexical factors, most notably word frequency, are well-known to condition phonetic variation. While word frequency has been reported to influence other acoustic variables (Jurafsky, Bell, Gregory, & Raymond, 2000), it has not been investigated with respect to nasal coarticulation. Lexical frequency has generally been discussed in terms of the prediction that highly frequent words will be subject to greater speech reduction (e.g., Zipf, 1935). Frequent words tend to be produced with temporal reduction (Jurafsky et al., 2000; Bell, Brenier, Gregory, Girard, & Jurafsky, 2009), more contracted vowel spaces (Munson & Solomon, 2004), and greater final segment deletion (Raymond, Dautricourt, & Hume, 2006) relative to less frequent words. Consistent findings along these lines hold across both experimental studies (e.g., Fidelholz, 1975; Munson & Solomon, 2004) and corpus studies (e.g., Jurafsky et al., 2000; Bell et al., 2009). As mentioned earlier, nasal coarticulation is also differentiated based on other lexical factors, specifically, phonological neighborhood density (Scarborough, 2013). However, the effect of frequency on nasal coarticulation specifically has never been investigated. Given that other phonetic properties such as vowel dispersion are affected by neighborhood density in the same way as coarticulatory nasality is (Munson & Solomon, 2004), and simultaneously affected by frequency, we predict that nasal coarticulation should also be conditioned by lexical frequency. Our specific predictions about how frequency should affect nasal coarticulation rely on the two competing views of coarticulation discussed above. If coarticulation is positively correlated with hypospeech, that is, gestural reduction, we predict that higher frequency items, which are often observed with shorter vowels and more segmental reduction, should be observed to have greater nasal coarticulation. On the other hand, if coarticulation is positively correlated with hyperspeech, that is, increased gestural overlap co-occurring with increased gestural magnitude, then we expect to observe lower frequency items being produced with greater nasal coarticulation.

If coarticulatory nasality is susceptible to change over time and also conditioned by lexical frequency, it presents a new testing ground for predictions about the role of lexical factors in sound change. One stance is that lexical frequency is a primary driving factor in sound change. For example, usage-based theories predict that in a situation where there is fast-speech reduction or other phonetic fluctuation present in the speech signal, high-frequency words "will have more chances to undergo reduction and thus will change more rapidly" (Bybee, 2002: 271). There is some empirical support for this notion. For example, a phonetic study of Oprah's interviews found that her degree of monophthongization varied as a function of both referee type and word frequency, with stronger monophthongization in higher frequency words (Hay, Jannedy, & Mendoza-Denton, 1999). Similarly, it has been reported that the raising and fronting of /ɪ/ in the speech of Latina gang members is most accelerated in higher frequency words (Mendoza-Denton, 1997). Note that the Latina /ɪ/ case study is an example of a non-leniting change being more advanced in higher frequency words. Although a strong form of the prediction from these results might be that frequency effects drive sound change, a related and perhaps easier to demonstrate possibility is simply that sound change might appear first and most strongly in most frequent words. If so, this should be borne out in an interaction between the diachronic trajectory of a demonstrated change and the effect of lexical frequency on the changing feature.

Meanwhile, an alternative stance in sociolinguistics has held that socially-driven changes affect phonemes in a uniform fashion and any lexical frequency effects are independent of the trajectory of the change (Labov, 2010). Yet another approach takes a different stance on the relationship between social factors and linguistic factors in variation: modern neo-generative/exemplar 'hybrid' approaches allow word-specific and socially-driven pronunciation biases to originate from different mechanisms, and even social factors can be the stronger bias in storing phonetic detail in some cases (see e.g., Pierrehumbert, 2002 and German, Carlson, & Pierrehumbert, 2013 for discussion). Experimental evidence has garnered support for a model where social weighting of phonetic variation is separate from or, in cases where they interact, influences lexical factors. For example, dialect experience helps listeners in short-term lexical access but social prestige influences what phonetic forms of lexical items are stored in long-term representations (Sumner & Samuel, 2009). Additionally, the stylistic context in which a word is produced (i.e. careful or casual) influences whether a reduced form of the word facilitates lexical access or not (Sumner, 2013). These findings indicate that sociolinguistic factors can influence how lexical representations are stored, suggesting that social influences on changes in phonetic variation may impact the lexical influences.

The current study aims to explore the relationship between lexical and social influences on phonetic variation. Ultimately, a systematic examination of both the internal and external linguistic factors involved in a sociophonetic change is necessary in order to contribute meaningfully to the discussion about how these factors are related. We predict that the lexical factor of word frequency should influence degree of nasal coarticulation independent of external linguistic influences. Since the present study consists of a large-scale corpus investigation of coarticulation, we can investigate the lexical influences on phonetic detail in tandem with the social variables. The ultimate goal is to gain a better understanding of how these internal and external factors either interact or have independent influence on the subphonemic properties of natural speech over time.

2. Methods

2.1. Philadelphia Neighborhood Corpus

The data for this study come from the Philadelphia Neighborhood Corpus (Labov & Rosenfelder, 2011). This corpus is a collection of sociolinguistic interviews conducted between 1973 and 2013 under the auspices of a graduate-level sociolinguistic fieldwork course that has been taught annually or biannually at the University of Pennsylvania during that time period. The speakers recorded for the corpus are adult native Philadelphians interviewed in their own homes in the neighborhoods of Philadelphia. Following the sociolinguistic theory and methods described in Labov (1984), the interviews are particularly directed at eliciting narratives of personal experience to maximize the degree of informality in speech style.

There are over 1000 interview recordings of this nature in the PNC, 380 of which have so far been fully or partially transcribed. After being transcribed, the interview sound files are automatically forced-aligned to the transcripts at both the word and phoneme level using the FAVE-align component of the Forced Alignment and Vowel Extraction (FAVE) suite (Rosenfelder, Fruehwald, Evanini, & Yuan, 2011). FAVE-align is based on the Penn Forced Aligner (Yuan & Liberman, 2008) but has been further developed for improved performance with the false starts, laughter, background noise, and speaker overlaps that characterize naturalistic conversational speech.

While advances in automated formant measurement have allowed for the rapid analysis of diachronic changes in vowel quality across all 380 transcribed interviews from the PNC (Labov et al., 2013), the measurement of vowel nasality is not yet as technologically advanced. The Praat script for automated nasality measurement described in Section 2.3 substantially facilitates the process, but still requires continuous analyst oversight. Hence, a subset of the 380 interviews that are partially or fully transcribed was selected for nasality measurement.

2.2. Sample selection

2.2.1. Real-time samples: trend and pseudo-panel samples

Our primary goal in constructing a sample was to enable an investigation of possible community-level changes in coarticulatory vowel nasality across the decades of mixed real and apparent time that the corpus covers. Another possibility that must be considered in any such study of change, though, is change in the systems of individual speakers during their lifespans. Such a possibility is particularly plausible in light of the potential physiological effects of aging on the velum, although socially-motivated lifespan change is also an option. The nature of the corpus and its collection logically prohibits a perfectly orthogonal design in terms of speaker birthyear and age at time of interview. For instance, when data collection began in 1973, it was possible to interview an elderly speaker who was born before 1900 but not a young adult speaker who was born before 1900. Conversely, the most recent years of data collection have been able to include young adult speakers born in the 1990s but not, obviously, elderly speakers born in the 1990s. The result is a very high correlation between age and birthyear in the corpus as a whole, which makes it very difficult to differentiate between the possibilities of lifespan change and community change.

We handle this issue through two independent samples of speakers. One sample targets change over time at the community level by including all 46 available PNC speakers under the age of 25, whose birthyears range from 1949 to 1989. This sample is the basis of a trend study, allowing us to see any possible effect of birthyear as a predictor while age is essentially controlled. A separate and independent sample targets the possibility of change over the lifespan of individual speakers by selecting all 41 available PNC speakers born between the years 1940 and 1949, who range in age from 30 to 67 at the time of interview. This sample is comparable to a panel study, wherein individuals are re-interviewed at different ages, except instead of revisiting the same speakers it is the generation that is resampled as it ages. This pseudo-panel study allows us to see any possible effect of age as a predictor while birthyear is essentially controlled. Note that, although the nature of the PNC as a whole blurs the lines between real and apparent time, both samples are best understood as presenting a real-time view of potential change because in both cases the range of ages/birthyears is made possible by the existence of a range of interview years. The trend study is achieved through the resampling of a certain-aged slice of the population over four decades, while the pseudo-panel study is achieved through the resampling of a specific cohort over four decades. Socially, the speakers in these samples predominantly represent the upper-working-class Irish and Italian

Table 1
Trend (real-time) sample: PNC speakers age 25 and under by sex and binned year of birth.

Year of birth	Female	Male	Total
1949–1954	7	4	11
1955–1960	2	3	5
1961–1966	2	6	8
1967–1972	3	4	7
1973–1978	1	2	3
1979–1984	1	5	6
1985–1991	4	2	6
Total	20	26	46

Table 2
Pseudo-panel (real-time) sample: PNC speakers born between 1940 and 1949 by sex and binned age at time of interview.

Age at interview	Female	Male	Total
30–35	6	3	9
36–41	6	4	10
42–47	2	3	5
48–53	2	0	2
54–59	4	0	4
60–67	6	5	11
Total	26	15	41

areas of South Philadelphia, which is one of the core neighborhoods that the corpus focuses on. The basic demographics of the trend and pseudo-panel samples are shown in Tables 1 and 2.

2.2.2. *Apparent-time sample*

The two samples described above provide two different real-time perspectives on change over time in nasal coarticulation. We will show in Section 3 that the assumption of the apparent-time hypothesis—namely, stability with age—holds in the pseudo-panel study. We therefore create one final dataset that includes the speakers from the real time sample and adds the remaining 18 speakers from the PNC with full-length interviews transcribed in their entirety (44 min or more). The addition of these 18 speakers extends the birthyear coverage from 1890–1991, a full century of apparent time. With a total of 105 speakers (46 + 41 + 18) and 8029 observations, the full sample not only covers a broad time range but also enables us to give a precise picture of lexical and segmental effects on nasality.

2.2.3. *Target words*

The current study focuses on monosyllabic, monomorphemic content words containing exactly one nasal segment extracted from the interviews with these 105 speakers. Word types are coded for position of the nasal segment relative to the vowel: preceding nasal, i.e., NV (e.g., *mad*), and following nasal, i.e., VN (e.g., *home*). The NV word types present the opportunity for carryover nasal coarticulation while the VN types present the opportunity for anticipatory nasal coarticulation. As will be discussed in Section 2.3, high vowels elude accurate acoustic nasality measurement, so words containing high vowels are excluded. The data set from the trend sample consists of 111 word types containing a nasal segment, represented by 2638 tokens; the data set from the pseudo-panel sample consists of 120 word types containing a nasal segment, represented by 3334 tokens. The final full data set consists of 163 word types containing a nasal segment, represented by 8029 tokens.

2.3. *Acoustic nasality (A1–P0)*

The lowering of the velum during vowel nasalization acoustically couples the nasal passages with the oral cavity, introducing nasal resonances in addition to the oral ones. These nasal formants fall in relatively predictable and stable frequency ranges, with the lowest nasal formant around 250 Hz and the second nasal formant around 900 Hz (Chen, 1997; though see further discussion of nasal formant frequencies below). As nasality increases, the relative amplitude (in dB) of these nasal formant peaks increases. In addition, the amplitude of the oral formant peaks, especially $F1$, tends to decrease. Thus the difference in amplitude between one of the nasal formants and $F1$ gives us a relative quantitative measure of nasalization: $A1$–$P0$ dB (where $A1$ is the amplitude of the $F1$ harmonic peak and $P0$ is the amplitude of the lowest nasal peak).

The low $F1$ of high vowels can obscure the lower nasal peak ($P0$) (Chen, 1997). Therefore, only non-high vowels were chosen for vowel nasality measurements in the current study. Note that the high-mid diphthong [eɪ] is raised to a high position in the Philadelphia dialect (Labov, 1994, 2001), necessitating its exclusion for the same reason as the true high vowels.

The spectral characteristics of orality and nasality are illustrated in Fig. 1, which compares an oral and a nasalized English vowel from one speaker measured for this study. The spectrum in Fig. 1a is taken from the vowel in the word “bad”. The amplitude of first formant peak ($A1$) is greater than the ostensible nasal formant peak ($P0$). Meanwhile, in the spectrum shown in Fig. 1b, from a

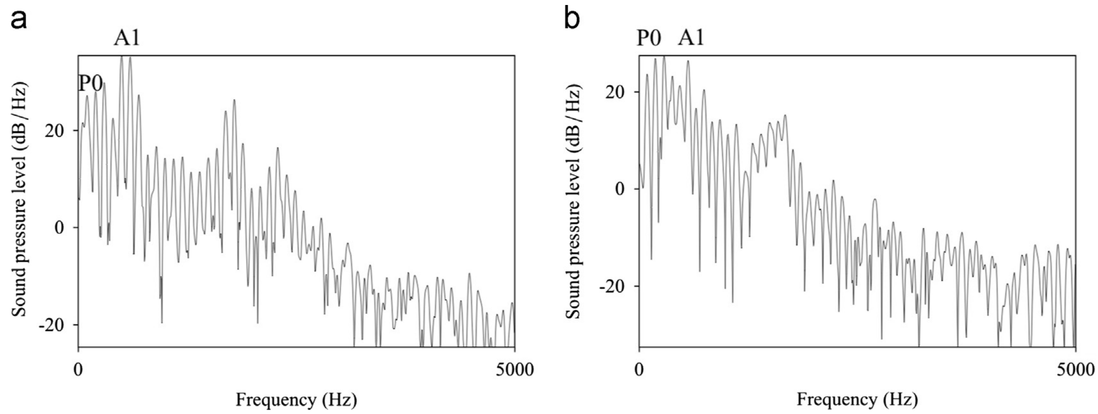

Fig. 1. Spectra for an oral vowel (from the word "bad") (a) and for a nasal vowel (from "mad") (b) from a male speaker in this study.

nasalized vowel in the word "mad", the first formant peak has decreased in amplitude while the nasal formant peak has increase in amplitude. Note that as nasality increases, *A*1 decreases and *P*0 increases, so a smaller *A*1–*P*0 indicates greater nasality.

For each measurement the boundary between the nasal and a vowel segment, which was placed automatically during forced alignment, was verified and hand-corrected as necessary. The accurate boundary was taken to be the point at which there was an abrupt reduction in amplitude of the higher formant frequencies in the spectrogram. An abrupt change in amplitude in the waveform, along with simplification of waveform cycles, was used to verify these measurements. These criteria were used for both VN and NV sequences (but with the waveform cues in reverse order for the latter). All *A*1–*P*0 measurements were made automatically, using a Praat script, at the midpoint of each vowel. In addition to nasality, vowel duration was measured automatically for each word from the hand-corrected phone tier of the Praat TextGrid.

The use of *A*1–*P*0 as a spectral measure of nasality does have limitations. For example, the frequency of *P*0 varies across speakers due to the resonant properties of each individual's nasal cavity, with *P*0 frequency locations reported across prior studies ranging from 250 to 450 Hz (Chen, 1997; Johnson, 2003; Stevens, 2000). With that in mind, we took several precautions during token selection and measurement verification in order to have as reliable a dataset as possible given the sensitive nature of spectral nasality. Specifically, as mentioned above, only words containing non-high vowels were extracted from the corpus, giving us confidence that the vowels contain an *F*1 higher than 450 Hz which would not interfere with the lower nasal formant. Furthermore, the harmonic status of *P*0 (either as *H*1 or *H*2) was verified to conform with what is expected based on gender/pitch characteristics of each speaker (i.e., *P*0 tends to be H1 in individuals with a higher fundamental frequency, for example women, while *P*0 tends to be H2 in individuals with a lower fundamental frequency) (for discussion, see Klatt & Klatt, 1990: 853). In addition, the frequencies of *P*0 and *F*1 were verified to ensure that they were appropriate for a given speaker and a given vowel quality.

We could have also looked at another measure of acoustic nasality in this data set: the ratio of the oral formant peak amplitude to the second, higher frequency nasal peak amplitude (=*A*1–*P*1). The frequency of the second nasal peak has been reported to fall between 900 and 1200 Hz (Chen, 1997; Johnson, 2003; Stevens, 2000) and even as high as 1300 Hz (Pruthi, Espy-Wilson, & Story, 2007). However, there are three principled reasons why we do not feel confident in reporting and drawing conclusions from *A*1–*P*1 measurements. First, the frequency of *F*1 varies considerably within a given vowel category, from a given speaker. In selecting the set of vowels for the present study, we took care to only select non-high vowels, where even a variable *F*1 is sure to be higher than 400/450 Hz and not interfere with *P*0. However, when identifying *P*1, *F*1 can often obscure *P*1 and result in a spurious measurement. Secondly, and relatedly, it is much harder to select an appropriate set of vowels for precise *A*1–*P*1 measurement. While we used the principle of selecting only non-high vowels for accurate *A*1–*P*0 measurement, the vowels appropriate for *A*1–*P*1 are even more constrained: to avoid the *F*1 or *F*2 peak from obscuring the nasal peak we would have to be limited to only higher, fronter vowels and only individuals in the lower range of *P*1. The current data set of words containing non-high vowels is not suited for accurately measuring *A*1–*P*1. Finally, the frequency of *P*1 can vary largely without an absolute lower limit. On the other hand, the frequency of *P*0 is constrained by being one of the first several harmonics. Note that even the predominantly predicted ranges of frequency locations of *P*0 (200–450 Hz) and *P*1 (900–1300 Hz) are not comparable: *P*1 has a reported potential range nearly twice the size as that for *P*0. These differences make *P*1 inherently harder and less accurate to identify than *P*0.

2.4. Model design

Linear mixed effects modeling is a powerful tool that allows for verification of statistical significance while testing and controlling for effects of multiple variables. In a mixed effects model, predictors that are nested by participant or item (for example, birthyear is uniquely determined by speaker identity) can be included as fixed effects, which get estimated as traditional regression parameters, while the nesting predictors are included as random effects that are allowed to vary around a normal distribution in order to account for speaker or item idiosyncrasy (Baayen, Davidson, & Bates, 2008).

We fit three linear mixed-effects models, one to each sample: trend, pseudo-panel, and apparent time. Each model is fit using the lme4 package (Bates, Bolker, Maechler, & Walker, 2013) in R. Traditional *p*-values are known to be difficult to estimate accurately from linear mixed effects models because the degrees of freedom are undetermined when random effects are included. As an alternative approach to assessing how much confidence we should have in individual parameter estimates, we use the languageR package (Baayen, 2011) to produce Highest Posterity Density intervals and their associated probabilities based on Markov Chain Monte Carlo sampling. The interpretation of the *p*-value from this Bayesian approach to significance testing is actually more intuitive than its traditional frequentist counterpart: there is a 95% chance that the true mean lies between the lower and upper bounds of the confidence interval.

In Sections 2.4.1–2.4.4 we justify our selection of the independent predictors in the models based on previous documentation of their influence on phonetic implementation.

2.4.1. Frequency

The SUBTLEX frequency norms that we use are drawn from 51 million words of English movie subtitles. The SUBTLEX norms have been shown to predict lexical decision and naming reaction times more accurately than other available frequency measures (Brysbaert & New, 2009), suggesting that they will also provide a more useful basis for understanding more complex behavioral implications of frequency. Frequency counts per million words for each token are log transformed and centered across each sample.

We also include two interaction terms involving frequency: coarticulatory direction by frequency, and birthyear by frequency. The former interaction tests the possibility that word frequency may have differential effects on anticipatory and carryover coarticulation, while the latter is the crucial test of the prediction that change is led by high-frequency items.

2.4.2. Vowel-conditional nasal probability

Phonotactic probability is the frequency with which a segment or sequence of segments occurs in a given position in all the lexical items of a language. Like word frequency, phonotactic probability has been shown to affect word production. Words with high phonotactic probability are spoken more quickly than words with low phonotactic probability (Vitevitch & Luce, 2004), as are nonwords (Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). These differences are often attributed to the difficulty of articulatory planning for low phonotactic probability items relative to those with high phonotactic probability.

While the effects of fine-grained phonotactic probability are robust, for the purposes of this study we employ a coarser metric of segment statistics. In line with our focus on degree of nasal coarticulation, we include as a predictor a measure of the likelihood that an adjacent segment is a nasal consonant. A nasal-conditional probability metric captures the frequency with which, given a vowel phoneme, a nasal segment either precedes or follows for all the lexical items in the language, which is reminiscent of the original notion of the likelihood that one element predicts another (Miller & Selfridge, 1950). Specifically, we use the probability of the preceding segment being a nasal consonant as the phonotactic probability for words in the carryover condition, and the probability of the following segment being a nasal consonant as the phonotactic probability for words in the anticipatory condition. These probabilities are calculated over the lexical items in the CMU Pronouncing Dictionary (Weide, 1998), with lexical items with a SUBTLEX frequency count of 0 excluded to ensure that the estimates are not biased by the huge number of obscure proper names in the CMU dictionary. We use this nasal-conditional probability measure to assess whether the likelihood of an adjacent segment being any nasal phoneme might affect the degree to which a vowel is nasalized.

2.4.3. Phonological neighborhood density

Phonological neighborhood density is a measure of the number of lexical neighbors for a given word. Neighbors are defined as words that differ from the target word by the addition, deletion, or substitution of a single phoneme (Luce, Pisoni, & Goldinger, 1990). Nasal coarticulation has been shown to vary systematically in words depending on the number of phonological neighbors: words with many neighbors are produced with a greater degree of vowel nasality than words with fewer phonological neighbors (Scarborough, 2013).

Frequency-weighted neighborhood density (FWND), defined as the summed log frequencies (SUBTLEX, Brysbaert & New, 2009) of a word and its neighbors, was calculated for each lexical item in our samples (for example, the word “snob” has eight monosyllabic phonological neighbors in English and their summed log frequency is 14.4, while the word “son” has ten neighbors but their FWND is 31.7). Neighbors were determined using the Hoosier Mental Lexicon (Nusbaum, Pisoni, & Davis, 1984), their frequencies drawn from the SUBTLEX norms (Brysbaert & New, 2009) and log-transformed, and the summed log frequencies centered across each sample.

2.4.4. Other linguistic fixed effects

Vowel height is included as a binary categorical variable, either low or mid vowel, since nasality has been shown to have the most substantial acoustic influence on *F*1 (Delattre, 1954; Krakow et al., 1988). Additionally, we include the log of vowel duration in milliseconds and the coarticulatory direction (carryover or anticipatory) from the nasal segment in the token. Sum contrasts are used for vowel height and coarticulatory direction because there is no clear default value.

2.4.5. Speaker-specific fixed effects

The apparent time model also includes as fixed effects the speaker-specific properties of sex (a binary categorical variable), age (at time of interview), and birthyear. Age and birthyear are centered for each sample at speaker, rather than token, level prior to residualization and polynomial fitting. As with vowel height and coarticulatory direction, speaker sex does not have a default value and therefore is fit using a sum contrast.

Visual inspection of the real-time patterns relating acoustic nasality to birthyear (in the trend study) and age (in the pseudo-panel study), as discussed in Section 3.1, gives us reason to believe that these effects may not be linear. We therefore compute orthogonal polynomials using the *poly*() function in *R* in order to be able to include the quadratic and cubic terms for birthyear (in the trend study) and age (in the pseudo-panel study).

In the apparent-time sample, as discussed in Section 2.1, speaker age and speaker year of birth are necessarily related given the nature of the corpus collection process. Age and birthyear in this sample have a Pearson correlation of −0.87 and variance inflation factors (VIFs, which assess multicollinearity in the apparent-time model without random effects) of 3.88 and 3.91, respectively. Multicollinearity, or non-independence of predictors, is a serious problem for regression because it violates the assumption of predictor orthogonality, making it impossible for the model fitting procedure to correctly attribute variance to one predictor or the other. To mitigate the potentially misleading influence of multicollinearity, we residualized age by birthyear (in the apparent time sample only). In residualization, one member of a pair of multicollinear predictors is taken as a baseline (here, birthyear) and the other predictor (here, age) is regressed linearly on the values of the baseline. The values of the second predictor are then replaced in the model by the residuals of this regression, which are by definition strictly orthogonal to the baseline predictor values (Gorman, 2010). The choice of birthyear as the baseline for residualization was made in light of the finding in Section 3.1 that there is a significant birthyear effect in the trend sample but no evidence for an age effect in the pseudo-panel sample. In other words, given that we have independent reason to believe that there is a true birthyear effect present, we assign birthyear as the primary predictor accounting for variation that could be attributed equally well to age or birthyear in the apparent time section of this study.

2.4.6. Random effect structure

We fit random intercepts for word and speaker in all three models. This random effect structure allows for the joint possibilities of speaker idiosyncrasy with respect to overall degree of coarticulation and lexical item idiosyncrasy with respect to overall degree of coarticulation. Although in principle individuals could also have idiosyncratic patterns of lexically-based differences in coarticulation, the inclusion of a random slope of word by speaker prevented the model from converging and thus was discarded.

3. Results

To summarize the preceding predictor descriptions: we fit three linear mixed effects models to acoustic nasality $A1–P0$ values (where lower values are more nasal) with random effects for word and speaker and fixed effects for speaker age, birthyear, and gender; log vowel duration; vowel height; coarticulatory direction (anticipatory/carryover); log word frequency; vowel-conditional nasal probability; frequency-weighted phonological neighborhood density; the interaction of log word frequency and coarticulatory direction; and the interaction of log word frequency and speaker birthyear.

3.1. Trend and pseudo-panel models

The isolated univariate effects on coarticulatory nasality of birthyear in the trend sample and age in the pseudo-panel sample are illustrated in Figs. 2 and 3, respectively.

Fig. 2, illustrating degree of nasality over time from the trend sample, shows a non-linear effect of birthyear on coarticulatory nasality. Between the years of 1950 and 1965, the degree of nasal coarticulation appears to increase over time slightly (slight decrease in $A1–P0$). Starting around 1965, however, there is a steep positive slope in $A1–P0$, indicating a trend towards a decreasing degree of coarticulatory vowel nasality. This trend continues until right before 1980, where the degree of nasal coarticulation increases again sharply ($A1–P0$ decreases). Note that although there are speakers with extreme values in either direction, if the seven speakers with $A1–P0$ means above 10 or below −2.5 are excluded from the graph, the shape of the curve remains the same.

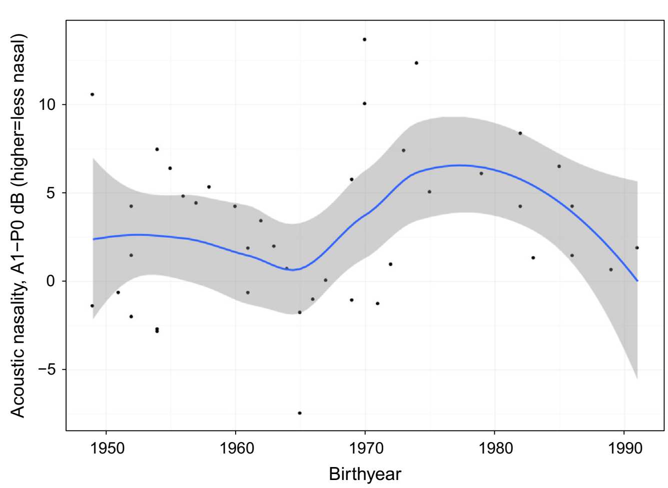

Fig. 2. Acoustic nasality ($A1–P0$; small = more nasal) speaker means by speaker birthyear, from the trend sample, fit with a loess curve.

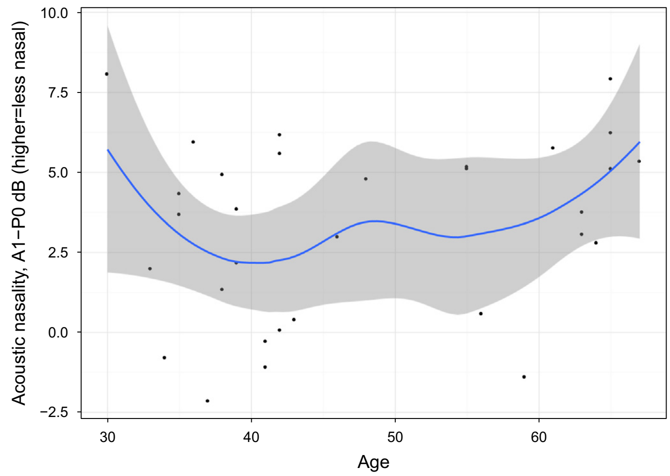

Fig. 3. Acoustic nasality ($A1$–$P0$) speaker means by speaker age, from the pseudo-panel sample, fit with a loess curve.

Table 3
Fixed effects parameters of the trend study model. Bolded terms indicate significance at $p<0.05$.

	MCMC mean	*95% HPD lower*	*95% HPD upper*	*p-Value*
(Intercept)	2.53	1.35	3.72	0.0008
Sex—female	−0.49	−1.47	0.46	0.46
Age	−1.08	−3.42	1.25	0.48
Birthyear—linear	33.69	−21.24	92.16	0.38
Birthyear—quadratic	−3.91	−52.34	41.95	0.85
Birthyear—cubic	**−76.21**	**−128.69**	**−30.28**	**0.02**
Log frequency	−0.34	−1.09	0.46	0.44
Vowel height—low	−0.09	−0.44	0.25	0.66
Log vowel duration	**0.71**	**0.28**	**1.13**	**0.001**
Conditional probability	−3.31	−0.2	6.98	0.10
Direction—carryover	0.24	−0.29	0.8	0.45
Neighborhood density	−0.22	−0.82	0.36	0.51
Birthyear—linear$_*$Log frequency	3.23	−19.8	25.45	0.79
Birthyear—quadratic$_*$Log frequency	−16.73	−38.67	4.94	0.12
Birthyear—cubic$_*$Log frequency	−5.65	−27.11	15.61	0.56
Direction—carryover$_*$Log frequency	−0.46	−1.21	0.31	0.24

We interpret this to indicate that these extreme speakers, particularly the speakers with very low nasality ($A1$–$P0$ values above 10) clustered around 1970, are at the front edge of true changes that are permeating the community, rather than statistical outliers in the sense of falling at the far ends of a normal distribution with a stable mean. The age trend, shown in Fig. 3, appears similarly non-linear, but in a far less systematic way.

The MCMC means, 95% HPD intervals, and associated p-values from the trend study model are presented in Table 3. The predictors are presented in the same order as they were specified in the model. Factor levels are coded using sum contrasts, so that the interpretation of the effect sizes is as the difference from the mean of the effects of the factor levels and the level that is not presented explicitly is the sum of the other levels times negative one.

The model of the trend study on nasal coarticulation data includes a significant effect for the cubic birthyear term. This suggests that all three components of our preliminary observations on birthyear effects are likely to be true effects: people born between 1965 and 1985 are producing vowels with less nasal coarticulation (larger $A1$–$P0$), while people born both earlier and later in the century produce more nasal coarticulation (smaller $A1$–$P0$).[2]

Vowel duration is also a significant predictor of nasal coarticulation: longer vowels have a greater $A1$–$P0$ value (=less nasal). This vowel duration effect is straightforwardly consistent with articulatory understandings of coarticulation as segmental overlap—when segmental durations increase, the degree of overlapping articulations decreases (Lindblom, 1990). Midpoint coarticulatory measurements such as those used here, then, will be strongly susceptible to vowel duration. No interactions or other main effects reached the 5% significance level[3].

[2] Despite our concerns that $A1$–$P1$ is a more noisy and less reliable measurement of acoustic nasality than $A1$–$P0$, we did examine $A1$–$P1$ in the trend data set following a reviewer's suggestion. Descriptively, we observed similar patterns of decrease and increase in degree matching the trends in the $A1$–$P0$ data. Yet, indeed, the $A1$–$P1$ data set was more noisy: visual inspection of the data revealed a large number of suspicious measurements. Specifically, in the trend sample data set the percentage of tokens that have an overlapping $A1$ and $P1$ is 6% (not including instances where $F2$ overlapped with $P1$); meanwhile the percentage of tokens that have an overlapping $A1$ and $P0$ is 0%. Statistically, there is a much larger amount of variability in the $A1$–$P1$ data set ($A1$–$P0$ SD = 5.4 vs. $A1$–$P1$ SD = 8.8). Modeling these data did not yield a significant birthyear effect; given the above-mentioned factors that, a priori, would contribute to a larger degree of noise in $A1$–$P1$ we find it unsurprising that we were unable to statistically confirm these effects in $A1$–$P1$.

[3] One anonymous reviewer brought up the concern that differences in vowel amplitude might affect the $A1$–$P0$ measure. However, we have three specific reasons why we do not feel this concern is likely to be a major problem in the context of the current data: First, a recent controlled laboratory study (Scarborough & Zellou, 2013) which reported systematic

Table 4
Fixed effects parameters of the pseudo-panel model. Bolded terms indicate significance at $p<0.05$.

	MCMC mean	*95% HPD lower*	*95% HPD upper*	*p-value*
(Intercept)	2.97	1.95	3.98	0.0001
Sex—female	−0.51	−0.51	−1.33	0.22
Age—linear	12.72	12.72	−36.18	0.59
Age—quadratic	29.6	29.61	−16.87	0.21
Age—cubic	−11.95	−11.95	−53.93	0.58
Birthyear	0.33	0.26	−1.38	0.76
Log frequency	**−0.94**	**−1.59**	**−0.31**	**0.004**
Vowel height—low	**−0.33**	**−0.64**	**−0.01**	**0.05**
Log vowel duration	**1.67**	**1.28**	**2.03**	**0.0001**
Conditional probability	2.15	−0.91	5.11	0.16
Direction—carryover	0.39	−0.08	0.85	0.10
Neighborhood density	−0.16	−0.69	0.31	0.53
Birthyear$_*$Log frequency	−0.56	−1.26	0.12	0.11
Direction—carryover$_*$Log frequency	−0.5	−1.14	0.17	0.12

The finding that nasality changes in nasal contexts over time in this dialect has two possible explanations: (1) degree of nasal coarticulation, that is, degree of vowel nasality only in nasal consonant contexts, is changing or (2) degree of nasality, that is, general openness of the velum, in all consonant contexts is changing. We conducted a *post-hoc* test of these hypotheses with the 42 speakers with the greatest amount of data. From these speakers, we measured nasality $A1–P0$ following the same procedure outlined above, but on monomorphemic content words with no nasal consonant ($N=9297$). If the first explanation is correct, we would expect a non-significant birthyear predictor. If the second explanation is correct, it should be borne out by a significant birthyear predictor on a model run on $A1–P0$ values from oral tokens, indicating that degree of nasality in all consonant contexts is changing. We fit the same model structure as for the trend sample, excluding the predictors of vowel-conditional nasal probability and coarticulatory direction. In this model, there is no evidence for a significant effect of birthyear on acoustic nasality in oral contexts ($p>0.05$ for all three degrees of the cubic birthyear term). This post-hoc analysis, together with the trend study model, indicates that nasality degree in nasal contexts is changing rather than overall nasality in this dialect.

Table 4 provides the MCMC means, 95% HPD intervals, and associated *p*-values of the pseudo-panel study model.

The pseudo-panel model did not yield a significant main effect of age on nasality: as adult Philadelphians age their degree of nasal coarticulation does not appear to change. We do find a significant negative coefficient for word frequency, indicating that degree of nasal coarticulation increases as word frequency increases.

Vowel height is a significant predictor of nasal coarticulation with low vowels having a greater degree of coarticulatory nasality (lower $A1–P0$) than mid vowels. We attribute the vowel height effect to two causes. First, this is consistent with previous findings linking velum height to jaw height: in English the low vowel [a] is produced with a lower velum height than other oral vowels, even in non-nasal contexts (Moll, 1962; Clumeck, 1976). The relationship between velum height and jaw height is generally understood to derive from their intrinsic physiological connection: when the jaw is lowered as far as is required by a low vowel, the soft palate is physically pulled somewhat lower, too. Second, as several reviewers noted, the amplitude of $F1$ differs between mid and low vowels (Peterson & Barney, 1952) and this would impact the $A1–P0$ measure. However, see Section 4.2 for discussion of why this effect is present in the pseudo-panel sample, but not in the trend or apparent-time sample. Finally, there is again a significant main effect of vowel duration wherein longer vowels have a higher $A1–P0$ measurement (are less nasalized). No other main effects or interactions are significant at the 5% level.

3.1.1. Temporal dynamic nasality patterns in trend sample speakers

Based on our observation of nasality at vowel midpoints in speakers' data before and after the 1965 turning point, we hypothesized two possible scenarios for the change in coarticulatory degree: decreased nasality signals either a change in overall degree of nasalization (i.e. reduction of the magnitude of the velum-lowering gesture) or a change in the gestural timing of velum lowering during vowel articulation (i.e., less gestural overlap of the adjacent nasal). To explore these predictions, we revisited the five most-nasal trend sample speakers born between 1960 and 1965 (directly before the ostensible beginning of the change toward decreasing nasality) and the five least-nasal trend sample speakers born between 1970 and 1984 (during the period of lowest nasality). A subset of the original words, those containing only a post-vocalic nasal consonant (VN), was selected in order to focus on differences in articulation of anticipatory vowel nasalization. Vowel nasality ($A1–P0$) was then measured over three equidistant timepoints over the duration of the vowel in each word: a midpoint, an early point at approximately 25% of the vowel duration, and

(*footnote continued*)
within-speaker variations in $A1–P0$ across five different “clear” speech elicitations did not find a consistent relationship between acoustic nasality and vowel amplitude, suggesting that these two factors are linguistically orthogonal. Second, we do not have confidence that an RMS amplitude measure can be accurately measured in this corpus, as the data were collected across decades of numerous naturalistic sociolinguistic field interviews, not in a controlled lab setting where microphone distance from mouth and other within/across speaker factors could be controlled for. Therefore, we are not confident reporting any results controlling for amplitude. Nevertheless, even though we believed that including amplitude was not linguistically or scientifically appropriate for these data, we measured RMS vowel amplitude on the trend data set. We then put these measurements into a post-hoc trend data model as a fixed predictor testing the hypothesis that the birthyear effect on nasality could be a by-product of intensity or loudness changes in vowel production over time. Critically, this did not change the significance of the cubic birthyear predictor on degree of nasal coarticulation, indicating that the results reported in this study are independent of the influence of overall vowel intensity on acoustic vowel nasality.

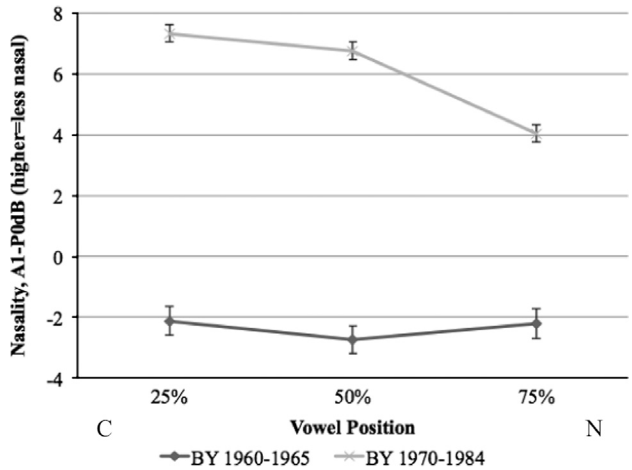

Fig. 4. Mean and standard errors of acoustic nasality ($A1$–$P0$; smaller = more nasal) over three timepoints in vowels preceding a nasal consonant (anticipatory coarticulation). Speakers binned by birthyear (5 speakers born between 1960 and 1965 and 5 speakers born between 1970 and 1984).

Table 5
Fixed effects parameters of the apparent-time model. Bolded terms indicate significance at $p<0.05$.

	MCMC mean	*95% HPD lower*	*95% HPD upper*	*p-value*
(Intercept)	2.66	1.83	3.49	0.0000
Sex—female	−0.43	−1.03	0.12	0.15
Age	1.22	−0.79	3.17	0.23
Birthyear—linear	*48.89*	*−5.06*	*105.59*	*0.09*
Birthyear—quadratic	2.33	−48.31	58.43	0.92
Birthyear—cubic	−12.93	65.16	41.36	0.64
Log frequency	**−0.75**	**−1.3**	**−0.15**	**0.01**
Vowel height—low	**−0.33**	**−0.59**	**−0.053**	**0.02**
Log vowel duration	**1.32**	**1.06**	**1.58**	**0.0001**
Conditional probability	1.38	−1.24	3.8	0.28
Direction—carryover	0.18	−0.31	0.64	0.44
Neighborhood density	−0.22	−0.66	0.21	0.32
Birthyear—linear⁎Log frequency	−15.08	−37.55	6.85	0.19
Birthyear—quadratic⁎Log frequency	−1.87	−23.97	20.13	0.87
Birthyear—cubic⁎Log frequency	11.79	−9.45	33.33	0.29
Direction—carryover⁎Log frequency	**−0.66**	**−1.2**	**−0.07**	**0.02**

a late point about 75% through the vowel duration. Fig. 4 presents the acoustic nasality averages over these words for the 10 speakers, binned by the earlier or later birthyear ranges.

Fig. 4, illustrating vowel nasality contours from three vowel timepoints, suggests a dynamic gestural account of the change. The speakers born earlier, who are more nasal, display a flat nasality curve, suggesting that the velum has lowered early during vowel production in anticipation of an upcoming nasal consonant. Meanwhile, from the speakers born later we observe a more dynamic nasalization contour. For these speakers, velum lowering does not appear to begin until after the midpoint of the vowel production. The overall observation of less nasality that we made for this group before, however, is not just an artifact of the midpoint measurements; even at the 75% point the two groups are still substantially different in their degree of nasal coarticulation.

3.2. Apparent-time model

The apparent-time model, combining the trend and pseudo-panel samples with auxiliary data for a total of measurements from 105 speakers, is provided in Table 5. Fig. 5 illustrates degree of nasal coarticulation over time from the apparent-time sample. The effect of word frequency on coarticulatory nasality in the apparent-time sample is illustrated in Fig. 6.

The apparent-time model testing the effects of all possible influencing lexical factors using the largest and most varied data set suggests that, all things being equal, higher frequency words have greater degree of vowel nasality, low vowels are more nasal than mid vowels, and longer vowels have less degree of nasality. There is also a marginally significant positive effect associated with the linear birthyear predictor (higher $A1$–$P0$ = less nasalization over 100 years' time). This is consistent with the trend model suggesting that people born later in the century are producing vowels with a lesser degree of nasal coarticulation. We suspect that the effect is linear in the apparent-time model, as opposed to the initially observed cubic effect, due to the larger range of birthyears in the apparent-time model (1890–1991); when the effect is diluted over a much larger time period, the general tendency of the change is statistically significant but the small dip in $A1$–$P0$ at the very leading edge of the change is not detected. Moreover, there is a significant interaction between frequency and coarticulatory direction: the difference in nasality between high and low frequency words is greater in anticipatory nasal contexts than in carryover contexts. No other main effects or interactions are significant.

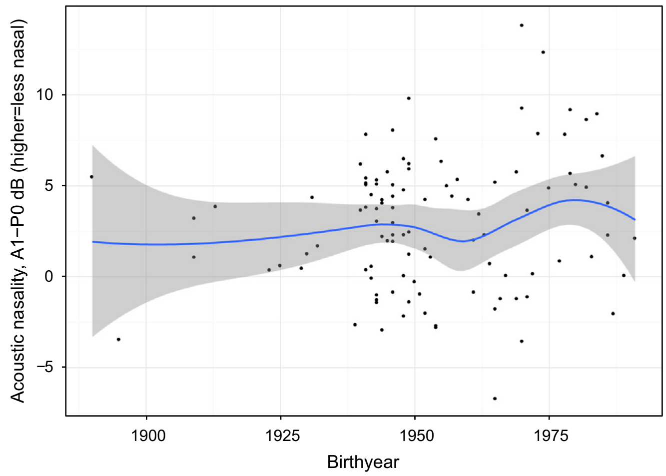

Fig. 5. Acoustic nasality ($A1$–$P0$) speaker means by speaker birthyear, from the apparent-time sample, fit with a loess curve.

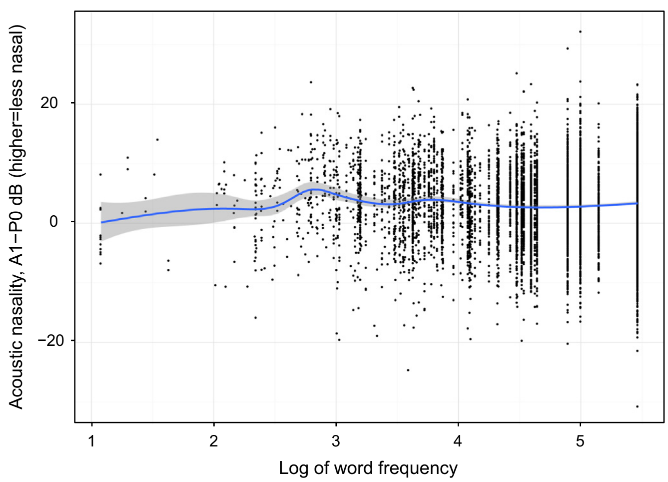

Fig. 6. Acoustic nasality ($A1$–$P0$) token measurements by log word frequency, from the apparent-time sample, fit with a loess curve.

3.3. *Post-hoc correlation between frequency and duration*

Note that in the full apparent-time data set, frequency was computed as a significant predictor of $A1$–$P0$ wherein higher frequency words have greater degree of coarticulatory nasality (lower $A1$–$P0$). A final post-hoc analysis aimed to determine whether this result is related to, or the result of, the one of vowel duration. The idea is that the established finding of higher frequency items produced with shorter word and segmental durations in general might lead to greater degree of nasal overlap due to shorter consonant productions but equal degree of velum gesture. However, a Pearson correlation test indicates that there is no evidence for a linear relationship between frequency and duration in the data set ($R = -0.0004$, $p = 0.97$). The results of this post-hoc analysis support the conclusion that the influence of word frequency on degree of nasal coarticulation established in the above models is direct and indeed independent from any segment or word length reduction effect commonly found associated with higher frequency items (though not observed in the present data set).

4. Discussion

4.1. *Summary*

To summarize the relevant results in Section 3: the significant cubic effect of birthyear in the trend study, which controls age while varying birthyear, signals several community-level changes in degree of nasal coarticulation over time. The observed pattern is one of gradual increase in coarticulatory nasality in the speech of people born from 1950 to 1965, followed by a brief period of decrease in coarticulatory degree in the community between 1965 and 1980, ending with a reversal where speakers born after 1980 producing more nasal coarticulation again.

Meanwhile, there is no evidence for a main effect of age in the pseudo-panel study, which controls birthyear while varying age. In both the apparent-time model and the pseudo-panel model, the significant main effect of word frequency indicates that more frequent words show greater nasal coarticulation. There is no significant interaction between frequency and birthyear in any of the models.

The only significant interaction observed is between frequency and coarticulatory direction in the apparent-time model, wherein the difference between anticipatory and carryover nasality is greater in high frequency words. Further discussion of these novel empirical findings is taken up in the next section.

4.2. Nasal coarticulation changes

We discuss five main points based on the patterns of nasal coarticulation observed in the three corpus data sets for the present study.

First, the observed changes in degree of nasality as a function of birthyear in the trend sample are interpreted as community-level diachronic change in degree of subphonemic nasal coarticulation. The field of sociophonetics has experienced a huge amount of interest in exploring how English vowel systems vary in fine-grained ways across and within communities over time. Few studies have examined quantitative changes in coarticulation in this respect. The first goal of this study was to address this gap by investigating whether non-contrastive vowel nasality in English can be subject to change within a speech community. We suggest that the significant effect of birthyear reflects systematic, community-level fluctuations in degree of nasal coarticulation over time in the speech of Philadelphians. The novel observation in the current study of a nasality change in progress in conversational speech suggests that nasal coarticulation can fall under the purview of socio-dialectal change within a community, thereby supporting the increasingly-accepted view that speakers can perceive and control fine-grained phonetic detail.

Our second conclusion stems from the fact that we do not witness nasal coarticulation in the present study varying as a function of speaker age, suggesting that the diachronic effect is truly one of socially-driven change in the speech community over time as opposed to either a physiological effect of aging or a socially-motivated age-grading effect. We do not deny that nasal coarticulation may be malleable over the lifespan under certain conditions, as suggested by a recent finding of nasality changing within one individual (Kwon, 2013), but our results indicate that it is stable with age as the default case.

The third discussion point is that diachronic changes in degree of nasal coarticulation are neither deterministic nor unidirectional. The observation that nasal coarticulation both increases and decreases over different periods of time in Philadelphia is consistent with an interpretation that phonetic change in coarticulation degree is non-deterministic; there are fluctuations in coarticulatory nasality that are not consistent with a singular articulatory or speaker-driven motivation for phonetic change. Along similar lines, there are other reported instances of dialectal variation and change in articulatory gestural timing that may be analogous to the observed change in degree of nasal coarticulation found here. For example, Fourakis and Port (1986) demonstrate that the excrescent stop that occurs between a homorganic nasal and fricative cluster in most dialects of English (as in *France* [frænts]) is not found in South African English. This rules out an explanation for stop excrescence, at least of the English variety, that relies purely on universal articulatory demands. Relatedly, a study of Western Andalusian Spanish reports that the timing of pre-aspiration that usually occurs before voiceless stops has gradually been moving through the segment to become produced as post-segmental aspiration (Parrell, 2012). In other words, if we focus on the characterization of coarticulation as overlapping gestures of discrete phonological elements, there is evidence for gestural re-organization across dialects driven by non-universal forces. One possibility, then, is that our finding of decreases and increases in degree of nasal coarticulation over time is a result of a gradual change in the gestural timing of the lowering of the velum within a speech community. This possibility is supported by our *post-hoc* comparison of anticipatory nasal coarticulation over more vowel timepoints in speakers born before and during the critical years of the change. We observed that speakers born earlier have overall greater nasality with flatter nasalization contours, suggesting that velum lowering has started very early in the vowel. Meanwhile, speakers born later have much less overall nasality and the onset of nasalization appears to commence after the vowel midpoint.

Moreover, in comparison with previous discussion of coarticulation and sound change (cf. Ohala, 1993; Beddor, 2009), the domain of this sound change appears thus far to be purely phonetic. Unlike a change where increase in degree of coarticulation might lead to misinterpretation and subsequent phonologization of vowel nasality, a well-attested phenomenon, a decrease in the degree of nasality seems unlikely to trigger phonological reanalysis of the feature [nasal] because the vowels showing less nasality are already phonemically oral. It will be necessary to track the change in nasality across future decades of Philadelphian speech to ultimately determine whether it can fairly be characterized as actuated and remaining purely within the realm of phonetic implementation, or whether it triggers unanticipated phonological restructuring. Recall that our observation of changing nasal coarticulation over time in Philadelphia English is more complex than simple reduction in coarticulation: there is a period of reduction of nasality, after a period of increasing nasality; then, this trend reverses so that the very youngest Philadelphians now appear to be more nasal than their immediate predecessors. This dynamic trajectory bears some resemblance to the recent demonstration from Labov et al. (2013) that several changes in the quality of Philadelphia English vowels are unexpectedly changing course, with the raising of [aw] and fronting of [ow] reversing after the middle of the 20th century. Although the timing of these reversals do not align precisely, it is possible that they may be driven by similar forces of language change.

The fourth discussion point from this study is that lexical frequency is a language-internal factor that influences degree of coarticulatory nasality in naturalistic speech. The significant main effect of frequency in the pseudo-panel and apparent-time models, with more frequent words showing greater nasal coarticulation, is notably present while a post-hoc correlation between lexical frequency and duration was not demonstrated. While the finding of lexical frequency conditioning phonetic detail is not uncommon, it is often left unclear whether there is a mediating effect of duration (Bell et al., 2009; Jurafsky et al., 2000). Higher word frequency is often correlated with shorter segment and word durations (Jurafsky et al., 2000; Bell et al., 2009), which has led to it being associated with hypospeech. Recall that one of our predictions was that if coarticulation is positively correlated with hypospeech, that is, gestural reduction, then higher frequency items should be observed to have greater nasal coarticulation. However, the current study found higher frequency items to be pronounced with increased degree of nasal coarticulation *without* co-occurring durational reduction. We have been careful to show that the effects of frequency and duration on degree of coarticulatory nasality are independent effects. Munson and Solomon (2004) tease apart these effects in a similar way. They report that low frequency words have more expanded vowel spaces and longer vowel durations than high frequency words. However, as in the present study, a post-hoc analysis indicates there is no correlation between vowel duration and hyperarticulation.

Given the lack of relationship between frequency and duration, we hesitate to conclude that our results are probative of different theories of the relationship between lexical frequency and coarticulation. Munson and Solomon (2004) use their comparable results to argue that the vowel-space reduction observed in high frequency items is due to a reductive articulatory process associated with increased ease of articulation in these more commonly pronounced words. Munson (2007) suggests that the mechanism underlying such an effect is the greater resting activation level in higher frequency items, connected to the frequency effects in word naming, specifically that higher frequency items are produced after shorter delay latencies (see also Balota & Chumbley, 1985; Brown & Watson, 1987; Garlock, Walley, & Metsala, 2001). Alternatively, Bybee (2002) suggests that the mechanism at play is simply neuromotor practice leading to increased fluency of articulation, which might imply greater gestural overlap. In any event, in the absence of further empirical evidence we have no motivation to take a more nuanced position on the source of the frequency effect on coarticulation observed in the current study.

The suggestion that articulatory ease forms the link between frequency and gestural overlap is also possibly compatible with the significant interaction between frequency and direction, wherein the difference between anticipatory and carryover nasality is greater in high frequency words. It is well documented that word-final consonant reduction is a typical feature of high frequency words in spontaneous speech (Jurafsky et al., 2000). Additionally, it has been shown that nasal consonant durations in CVNC words are inversely correlated with the extent of the velum lowering gesture on a preceding vowel in English (Beddor, 2009). Given both of these previous findings, we suggest that the interaction of frequency and coarticulatory direction in the present study may be the result of a retiming of the velum gesture compensating for the weakening of final, but not initial, segments in higher frequency words. To be more specific, we speculate that word-final consonants undergo increased lenition as word frequency increases, but the velum-lowering gesture for nasal consonants, rather than decreasing in magnitude, re-aligns to start earlier during the production of the vowel. The result, since we are using midpoint measurements and therefore ‘catch’ a greater portion of the anticipatory coarticulation when it starts earlier, is a boost in the measured degree of coarticulation in anticipatory contexts over carryover contexts that does not happen in low-frequency contexts because they lack final consonant reduction. Yet again, without further evidence this remains speculation. We believe further research is needed examining the effect of word frequency on articulation of adjacent segments in order to draw more conclusive results on this issue.

Our fifth and final main discussion point is that the social effect of birthyear and the language-internal effect of lexical frequency, which were the primary targets of this study, appear to be independent influences on degree of nasal coarticulation. Critically, there is no significant interaction term in any of the models between birthyear and frequency, which signals that they are statistically independent. We suggest that the observed synchronic frequency effects result from cognitive mechanisms independent from the triggers and drivers of community-level change.

Notably, the main effect of frequency is conspicuously absent in the trend study model. We suggest that the observed sound change impedes our ability to observe such a frequency effect. During the most rapid period of change, which is that captured in the trend sample, there may be too much change-induced variability in nasality to detect smaller effects of frequency. Whether this obscuring is linguistically meaningful or merely a statistical issue requires further investigation. It may be a more general phenomenon, with diachronic changes in progress effectively leading to a masking of systematic fluctuations resulting from cognitive-linguistic mechanisms, or it may particularly reflect the competing directions of the change and the frequency effect. Crucially, we do not observe high-frequency words leading sound change; rather, the effect of frequency on phonetic implementation is obscured by the Philadelphia sound change of decreasing nasalization.

4.3. Further reflections

None of the models yielded a significant main effect of neighborhood density on degree of nasal coarticulation. Although a lack of significance is of course not conclusive, the failure of obtaining such an effect is somewhat striking given previous findings (e.g., Scarborough, 2013) of an increase in degree of nasality in words from more dense phonological neighborhoods. This discrepancy may result from the fact that the current study was limited to data from uncontrolled, spontaneous conversational data while data from previous studies were recorded in a controlled laboratory setting where words were presented in carrier phrases. Similar discrepancies in the effect of neighborhood density on other aspects of speech production have been reported across laboratory and conversational speech. For example, high neighborhood density words are consistently produced with greater degree of hyperarticulation than low neighborhood density words in laboratory studies (Wright, 2004; Munson & Solomon, 2004), while in a study of spontaneous conversation from the Buckeye corpus, the effect is reversed: *low* neighborhood density words are significantly more hyperarticulated than words from dense neighborhoods (Gahl, Yao, & Johnson, 2012). In the same study, Gahl et al. fail to find a significant effect of either single-phone or biphone positional probability, parallel to our result that nasal-conditional probability is not a significant predictor of degree of nasality in any model. This is in contrast to laboratory results on the effects of phonotactic probability (Vitevitch & Luce, 2004). We believe further research is needed to elucidate the inconsistent findings on neighborhood density and phonotactic probability patterns in studies of laboratory versus conversational speech. Understanding the relationship between speech in experimental conditions and speech between conversational partners not only is crucial to correctly interpreting experimental results but also may prove fruitful for clarifying models of speech representation and processing.

4.4. The origins of the change

While we can only speculate at this time about why societal-level changes in the degree of nasal coarticulation in the speech of Philadelphians have been actuated, there are a few candidate catalysts we would like to entertain as possibilities. First, Labov et al. (2013) report two shifts in the Philadelphia vowel system that begin in the early 20th century but then reverse shortly after the mid 20th century. The timing and trajectory of these changes bear some resemblance to the nasality changes we have documented here. One possibility, then, is that the sociocultural motivations driving the vowel quality changes observed by Labov et al. may also be at play in the actuation and transmission of the nasality changes. They suggest that these phonetic vowel quality changes are motivated at least in part by Philadelphians shifting to reduce their affiliation with Southern cities and thereby reposition themselves as a more Northern city (Labov et al., 2013: 60–62). While nasality has not been reliably reported as a significant social evaluation of Southern speech (Preston, 1996), further work on the empirical geographic distribution of coarticulatory nasality is merited.

A second possibility is that this change occurred essentially by chance. It has been suggested that the inherent variability found across speakers might be adopted as a change in the target of articulation if it happens to align with speaker social networks in a particular way. This argument has been supported by evidence regarding differing phonologization outcomes of s-retraction (i.e., ‘street’ [ʃtrit]) across English dialects (Baker, Archangeli, & Mielke, 2011). Baker et al. argue that natural inter-speaker differences in degree of coarticulation might lead to identification of innovative production targets. More specifically, actuation of sound change occurs when “inter-speaker variability is so great [in one direction] that some speakers actually produce a sound that can be perceived as a distinct target. Given the appropriate social conditions, this can be realized through another speaker adopting the novel target in his/her speech” (p. 351). The appropriate social conditions in their explanation involve the coincidental situation of extreme speakers at influential points in social networks. In other words, if the change in degree of nasal coarticulation does not originate from a shift in Philadelphians' regional affiliation from the south to the north, along with nasality being socially associated with these labels, then another alternative is that this is simply an arbitrary change in the articulatory target of the velum lowering gesture in vowels adjacent to nasal consonants due to a build-up in socially influential but naturally less nasal-sounding people at some point in time.

5. Conclusion

The main finding of this study is that the degree of nasal coarticulation in the Philadelphia speech community has undergone systematic changes over time, with a general tendency towards Philadelphians becoming more nasal over time, but with a small window between the birthyears of 1965–1980 where speakers actually became less nasal. We suggest that this observation reflects a shift in the gestural timing of velum lowering associated with nasal consonants such that their coarticulatory effects impinge to a greater or lesser extent on adjacent vowels. A second important empirical result from this study is that there is a positive relationship between word frequency and degree of nasal coarticulation. The independent effects of birthyear and lexical frequency point to models of speech production where lexical effects are independent from social factors conditioning variation. Changes in stored phonetic implementation targets for phonemes can be socially-driven.

Importantly, the diachronic coarticulatory change observed in the current study is non-deterministic: there are fluctuations in degree of coarticulatory nasality as a function of time that cannot be characterized as occurring only in one direction of change. The empirical observation of changes in coarticulatory nasality supports the view that coarticulation is not simply an articulatory universal but rather is malleable and controllable. This study thus constitutes further evidence that speakers precisely perceive and make meaningful use of systematic subphonemic variation.

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