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Secondary Phonetic Cues in the Production of the Nasal Short-a System in California English

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Abstract

A production study explored the acoustic characteristics of /æ/ in CVC and CVN words spoken by California speakers who raise /æ/ in pre-nasal contexts. Results reveal that the phonetic realization of the /æ/-/ɛ/ contrast in these contexts is multidimensional. Raised pre-nasal /æ/ is close in formant space to /ɛ/, particularly over the second half of the vowel. Yet, systematic differences in the realization of the secondary acoustic features of duration, formant movement, and degree of coarticulatory vowel nasalization keep these vowels phonetically distinct. These findings have implications for systems of vowel contrast and the use of secondary phonetic properties to maintain lexical distinctions.

Index Terms: short-a, allophony, nasality, sound change

1. Introduction

1.1. Contrast Reduction

In some cases, changes in vowel positioning result in reorganization where two previously contrastive sounds become indistinguishable, or merge. Well-studied mergers in American English include the *cot/caught* merger of low back vowels /ɑ/ and /ɔ/ in western and midlands US dialects and the *pin/pen* merger of pre-nasal /ɪ/ and /ɛ/ found in US South and West dialects [1]. Mergers lead to the neutralization of certain lexical distinctions. Since the maintenance of lexical contrasts is linguistically and communicatively important, it is predicted that this pressure might counter the pressure toward sound change that would lead to a merger, e.g., [2]. Indeed, cross-linguistically, mergers are less likely to occur if the sounds have a greater lexical-functional load, i.e., contribute more to distinguishing words [3]. This indicates that maintaining minimal pair contrasts is one factor that can predict when and how sound changes might occur.

The vowel change vs. reduction of contrast tension can also be mediated through recruitment of secondary phonetic cues which keep vowels distinct despite substantial overlap in formant frequencies. For example, [4] observe that nucleus formant frequencies of *pin/pen* vowels for a Midland talker completely overlap, indicative of a merger; however, formant movement for these vowels is quite distinct (/ɛ/ has a forward-moving offglide while /ɪ/ has a backward-moving offglide). They argue that the distinction between words like *pin* and *pen* can be maintained via these differences in spectral change. Distinct formant trajectory patterns have also been reported for the low back vowels (subject to the *cot/caught* merger) in Southern American English [5], further showing the role that formant movement patterns can play in maintaining a distinction between vowels. (See also [6] for work on how vowel-inherent spectral change varies across US English.) Speakers can also use voice quality and temporal features to maintain contrast when two vowels move closer together. For instance, for some regions with a *caught/cot* merger, speakers produce these vowels as distinct in either voice quality (/ɔ/ breathier than /ɑ/) or duration (/ɑ/ longer than /ɔ/) [7], [8]. Another observation is that American vs. Jamaican English vary in use of duration in maintaining vowel contrasts [9].

The current paper focuses on phonetic variation in the “nasal system”, characterized by /æ/ raising before nasal consonant codas only [1]. This raised /æ/ variant is produced with a higher and fronter tongue position. The nasal system is exemplified in many Western US English dialects, including in dialects in California, where vowel lowering and backing in oral contexts are also reported, e.g., [11]. This leads to a split in the phoneme /æ/, but a potentially reduced distinction between the pre-nasal raised /æ/ and e.g., /ɛ/ in the same context. In the current study, the extent of contrast reduction between /æ/ and /ɛ/ in pre-nasal position for formant values is evaluated, and the role of secondary acoustic characteristics in maintaining this distinction in production is examined.

1.2. Nasality, raising, and sound change

Relevant to the case of pre-nasal /æ/ raising is the fact that the conditioning environment is a nasal consonant, which creates a context for nasal coarticulation. Nasal coarticulation is the overlap of nasality produced on a vowel preceding a nasal consonant due to anticipatory velum lowering. [12] argues that sound change often results from an ambiguous relationship between the acoustic output and the underlying structure, due to coarticulation, where a single acoustic feature can have multiple potential interpretations as to its articulatory source.

Vowel nasalization results from the acoustic coupling of the resonances of the nasal passage with those from the oral cavity, yielding a complex acoustic signal representing both cavities’ resonant frequencies [13]. This spectral complexity can lead to ambiguity in the acoustic cues in a nasalized vowel. For example, the presence of a lower frequency nasal resonance, along with weakened oral resonances [14], has the additive effect of skewing the “spectral balance” towards the lower frequency ranges in nasalized vowels [15]. This can result in an acoustic-perceptual lowering of F1 [16]. In other words, the acoustic effects of vowel nasalization might be misattributed by a listener to a different intended vowel quality. Indeed, nasalized low vowels are perceived as higher than their oral counterparts [16], [17]. Speakers have also been shown to produce systematically different tongue positions for nasalized vowels relative to non-nasalized counterparts [18], [19], reflecting the phonologization of distinct oral and nasal vowel qualities that originated in the misattribution of nasalization effects as tongue height variations [18].

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The acoustic effects of nasalization on perceived vowel height explain the allophonic raising of /æ/ in pre-nasal contexts. Phonologization of the coarticulatory effects on /æ/ yields distinct pre-nasal and oral formant patterns. However, coarticulation-induced vowel raising also results in reduced acoustic distance between pre-nasal /æ/ and /ɛ/, since a raised low vowel would move toward or even impinge upon the space for a higher vowel. In such a case, secondary cues, perhaps including differences in degree of nasalization, might serve to compensate for the otherwise reduced contrast.

The degree of nasal coarticulation realized on vowels is indeed known to be subject to variation and change across groups of speakers [20], [21]. Further, in controlled laboratory settings, speakers have been shown to systematically vary the degree of produced nasal coarticulation in words and contexts that might be prone to confusion, suggesting that coarticulatory patterns can be used by listeners to identify words [22]–[24]. If degree of nasality is a learned but changeable aspect of the phonetic grammar and can be recruited as a systematic feature to enhance perception, this opens the possibility that it could be exploited to manipulate the acoustic distance between two vowels that have otherwise become more similar in formant space.

1.3. Current study

The multidimensional nature of vowel contrast and its relation to sound change is explored in the current study. Prior work has demonstrated that Californians exhibit a raised /æ/ allophone in pre-nasal contexts which is distinct from /æ/ in other contexts [11]. We explore various dimensions of this nasal system, including F1/F2 measurements both statically and dynamically across the vowel, vowel durations, and degree of nasalization due to coarticulation. Despite the fact that pre-nasal /æ/ is raised, leading to potential reduction in formant space between /æ/ and /ɛ/, we show that while the distance between these vowels is indeed reduced in F1/F2 acoustic space at static points within the vowel, these vowels are actually distinct with respect to their dynamic realization in formant space, and with respect to secondary dimensions: their durations and degree of nasality (coarticulation).

2. Methods

2.1. Participants and Materials

Thirty-two native speakers of American English (age range: 18-23 years old, mean age: 19.5; 26 F), participated in the production study, recruited through the UC Davis subjects' pool. Participants were all native to the West Coast of the US.

The study wordlist included 36 monosyllabic English words comprising /æ/-/ɛ/ minimal pairs, with equal numbers of words with oral and nasal (alveolar and bilabial) codas. (e.g., the type "bad", "ban", "bed", "ben".) Four sets of phonetically matching words containing the back vowels /ɑ/ and /ʌ/ were also included, for comparison. Both duration and degree of nasalization are known to be affected by intrinsic vowel height [25], so the comparison of the production patterns from a mid-low back vowel phoneme pair with those from /æ/ and /ɛ/ allows us to evaluate the nature of secondary characteristics as a learned part of the vowel system, rather than due to intrinsic articulatory factors. Test words were interspersed with 48 monosyllabic filler words. Acoustic recordings were made using a Shure WH20 XLR head-mounted microphone and digitally sampled at 44-kHz in a sound-attenuated booth. Each word was produced two times in the carrier phrase "__, the word is __".

2.2. Measurements

Target words were segmented automatically using FAVE [26] then vowel boundaries were hand-corrected. The onset and offset of the vowels were considered to be the points at which there was an abrupt change in amplitude of higher frequency formants in the spectrograms; along with simplification of waveform cycles, this cue was used to corroborate vowel boundaries, especially for words with nasal codas.

Three types of acoustic measurements were obtained from vowels: vowel duration, F1-F2 values, and spectral nasality measurements. F1 and F2 measurements were taken at the midpoint (50% of vowel duration) for each target vowel, and at 20%, 35%, 65%, and 80% intervals of vowel duration. Two additional formant frequency measurements were computed: between-pair Euclidean distance and within-vowel spectral rate of change. First, Euclidean distance between front vowel /æ/-/ɛ/ minimal pairs was calculated for each speaker using log mean normalized Hz of F1 and F2 at each time point in the vowel. Minimal pairs were matched across positions within a trial response. Secondly, spectral rate of change (ROC) was measured following [27]. Each vowel was divided into four vowel sections (e.g., 20%-35%, 35%-50%, etc.). Within each section, the vowel's trajectory length (TL), or amount of spectral change in F1/F2 space, was calculated; the TLs for the four sections were summed to generate an overall TL. Spectral ROC was calculated by dividing overall TL by 60% of the vowel's duration. Summed overall TL is a good characterization of spectral movement, since it captures both curved and linear formant trajectories. Spectral ROC normalizes TL for vowel durations, since vowels with longer durations tend to display greater spectral movement [27].

Degree of nasalization was measured acoustically as A1-P0, or the difference in the amplitudes of the first formant peak (A1) and the lowest frequency nasal peak (P0) [14]. As nasalization increases, the amplitude (in dB) of the nasal formant peaks increases, while the oral formant peaks tend to be damped. The relative difference, then, of the oral and nasal formants, or A1-P0, provides a quantifiable measure of nasalization which *decreases* as nasality increases. A1-P0 measurements were made at vowel midpoint.

3. Analysis and Results

Figure 1 provides mean formant values for /æ, ɛ, ɑ, ʌ/ in each context at five time points, 20%, 35%, 50%, 65% and 80% of vowel duration (color varies from dark to light over vowel time course). /ɑ/ and /ʌ/ are included to provide perspective on the vowel space. As seen, pre-oral /æ/ is lower and backer than pre-oral /ɛ/ at all timepoints; in fact, /æ/ almost aligns in backness with /ʌ/, supporting the observation that /æ/ is backed in this dialect region. However, pre-nasal /æ/ is substantially higher and fronter in the vowel space and considerably close to /ɛ/. Also, pre-nasal /æ/ partially overlaps with /ɛ/ for nearly the second half of the vowel duration.

All vowels show spectral movement over their duration. However, in CVC words, the change does not lead to overlap between phonemes at any timepoint. By contrast, examination of the formant patterns in CVNs reveals distinct formant trajectories for CæNs and CɛNs, and in particular, /æ/ in this context exhibits more monotonic movement, starting at a raised and fronted position and moving to a lower and backer position close to /ɛ/ at end. As a first step in assessing phonetic distance between the mid and low vowel pairs, Euclidean distances between /æ/-/ɛ/ of minimal pairs over the vowel time course were investigated. (Using log mean normalized formants [28]). Mean Euclidean distance values in Fig 2 indicate that, relative to their difference in CVC contexts at the beginning of the vowel, these minimal pairs are quite distinct. CæN and CɛN are further apart because the raising of pre-nasal /æ/ overshoots the position of /ɛ/. Yet, over the course of the vowel, the formant space distance between /æ/ and /ɛ/ pre-nasal words is reduced and in fact, the contrast between pre-nasal /æ/ and /ɛ/ is the most reduced, and most different from the pre-oral pair, in the second half of the vowel.

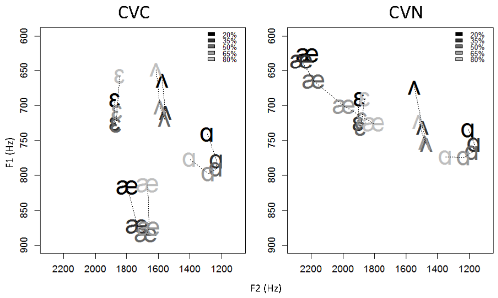

Figure 1: *Mean formant frequency values taken at 20%, 35%, 50%, 65% and 80% of vowel duration for front and back non-high vowels in oral (left) and pre-nasal (right) coda contexts.*

We fit a mixed effects regression model to the log mean normalized Euclidean distance data to test whether 1) the distance between /æ/ and /ɛ/ in pre-nasal position is reliably smaller than in CVC contexts and 2) the distance changes over the time course of the vowel. The model was run in R using the *lmer* function in the *lme4* package [29]. Estimates for degrees of freedom, *t*-statistics, and *p*-values were computed with the *lmerTest* package [30]. The Euclidean Distance model included two fixed effects. First, the predictor Nasality (two levels: Oral and Nasal) tested whether acoustic distance is smaller before nasal codas. Second, the Time predictor, tested whether these values change over time (values centered and scaled). The two-way interaction, between Nasality and Time, tested whether the change in acoustic distance between /æ/ and /ɛ/ in CVN words was reliably different than in CVCs. Random intercepts for subject and by-subject random slopes for the interaction of Nasality and Time were included. The model revealed only a significant interaction between Nasality and Time point [*F*(1, 30.7)=52.6, *p*<.001], corroborating the patterns illustrated in Fig. 2, that /æ/-/ɛ/ distance decreases over the course of the vowel duration in pre-nasal contexts, relative to in oral contexts where the distance increases over time.

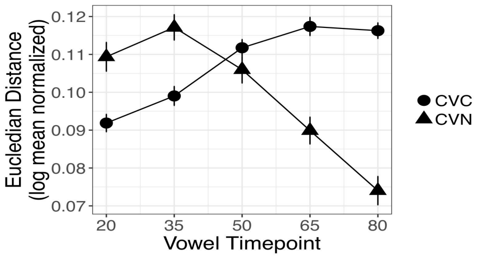

Figure 2*: Mean Euclidean distances, and standard errors, at 20%, 35%, 50%, 65%, and 80% of duration, for log mean normalized formants, between front /æ/-/ɛ/ minimal pairs.*

The Euclidean distance analysis reveals that in pre-nasal position, there is a reduction of the /æ/-/ɛ/ contrast. Yet, Fig 1 shows the formant trajectories for non-high, monophthongal vowels appear to be distinct. Spectral ROC measures for the vowels in each context, provided in in Figure 3. For /ɑ, ʌ, ɛ/, spectral ROC values are similar in nasal and oral contexts. In contrast, spectral ROC values are higher for pre-nasal /æ/, indicating increased formant movement compared to oral /æ/.

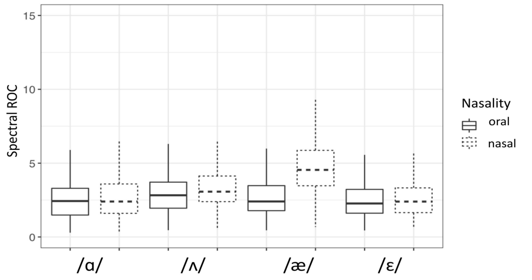

Figure 3*: Boxplots of Spectral ROC measures for* /ɑ, ʌ, æ, ɛ/ *before oral (solid lines) and nasal (dotted lines) codas.*

A linear mixed effects model was fit to the spectral ROC data consisting of two fixed effects: Vowel (two levels: /æ [baseline level] and ɛ/) and Nasality (two levels: Oral [baseline] or Nasal coda). A two-way interaction between the fixed effects was also included. Random intercepts for speaker were included in the model; models with a more complex random effects structure did not converge. A significant main effect of Vowel on spectral ROC was computed [*F*(1, 2204)=26.6, *p*<.001], indicating that /ɛ/ and /æ/ differed overall in the amount of formant movement exhibited. Nasality was a significant predictor of vowel spectral ROC [*F*(1, 2204)=94.3, *p*<.001] indicating that nasalized vowels have more formant movement than oral vowels. The higher spectral ROC values for /æ/ before nasal codas seen in Fig 3 significant, as indicated by an interaction between Vowel and Nasality [*F*(1, 220)=40.7, *p*<.001].

Vowel duration is also known to be a critical secondary feature in conveying certain vowel contrasts in English (e.g., [10], [25]). Therefore, we examine mean durations for /æ, ɛ, ɑ, ʌ/ before oral and nasal codas. Figure 4 shows average duration differences within low/mid minimal pairs across contexts. The duration difference between /ɑ/-/ʌ/ is smaller than that between /æ/-/ɛ/ in CVC and CVN words.

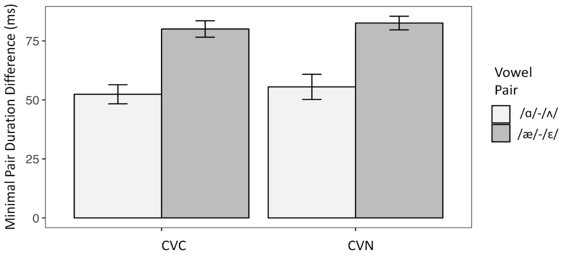

Figure 4*: Mean difference, and standard errors, of vowel duration (ms) between /æ/-/ɛ/ (dark) and /ɑ/-/ʌ/ (light) words.*

A linear mixed effects model run on duration differences included fixed effects of Vowel pair (front: /æ vs. ɛ/, back: /ɑ vs. ʌ/), Nasality of the coda (Oral, Nasal), and the two-way interaction between Vowel pair and Nasality, with full random effects structure. A significant main effect of Vowel pair [*F*(1, 611.3)=46.2, *p*<.001] indicates that the overall /æ/-/ɛ/ duration differences are larger (/æ/ is the longer vowel) than /ɑ/-/ʌ/ duration differences. Coda Nasality (p=.4) and the interaction between Vowel and coda Nasality (p=.9) were not significant.

We also consider the targeting of nasality for recruitment as an additional secondary feature. To compare coarticulation across vowels, nasality was calculated as a *relative* difference from oral (CVC) minimal pairs, shown in Figure 5. Across /ɑ, ʌ, ɛ/, degree of nasalization is relatively consistent. In contrast, /æ/ has a large CVC-CVN difference: /æ/ is realized with a greater degree of nasal coarticulation than other vowels in this context. A linear mixed effects model run on these data with a fixed effect of Vowel (four levels: ɑ [baseline], ʌ, ɛ, æ), which was a significant effect of Vowel [F(3, 640.8)=54.7, p<.001]. Pairwise comparisons indicate that relative nasality for /æ/ before nasal codas is greater than for other vowels.

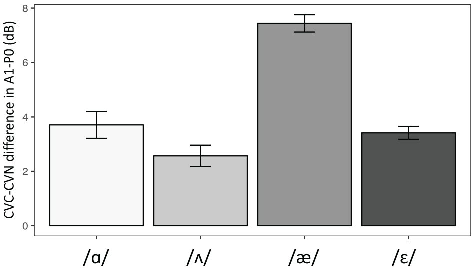

Figure 5*: Mean difference, and standard errors, in acoustic nasalization between CVC and CVN minimal pairs by vowel.*

4. Discussion

This study examined pre-nasal /æ/ in the California vowel system. Our production study demonstrated that pre-nasal /æ/-raising resulted in a reduction of the distance in formant space between /æ/ and /ɛ/. Inspection of other spectral and durational characteristics of these vowels revealed secondary acoustic properties that co-occurred with pre-nasal /æ/ raising: low vowels are longer in all contexts, and pre-nasal /æ/ showed both greater formant movement and a greater degree of coarticulatory nasalization at midpoint than pre-nasal /ɛ/. Our findings support the view that vowel contrast is inherently multidimensional and that speakers can recruit variation in multiple phonetic properties to maintain lexical distinctions.

The distinct formant trajectory patterns seen for pre-nasal /æ/ and /ɛ/ align with evidence that change in the spectral properties of vowels over time is a relevant feature of American English [6], [31]. In fact, formant movement has been shown to be involved in maintaining distinctions between other vowels that are partially merged, or even reduced [4], [5]. Thus, our results could indicate that formant movement is recruited and used to maintain vowel phoneme distinctions where formant contrast is reduced.

Pre-nasal /æ/ also had the greatest degree of acoustic vowel nasalization at midpoint, compared to the other vowels. A growing body of work indicates that patterns of nasal coarticulation are learned and available to speakers for use in encoding social, stylistic, or lexical patterns [20], [22]. That the nasality characteristics of pre-nasal /æ/ might be controlled and leveraged by speakers in our study is supported by the observation that /æ/ had the greatest degree of acoustic vowel nasalization. Further, these vowels were also longest in duration. Typically, in English, shorter vowels are more influenced by overlap with a following nasal consonant, and thus are produced with greater vowel nasality [32]. So, the greater nasalization in the *longer* vowel /æ/ suggests intentional targeting of that feature. We also do not find a difference in nasalization between /ɑ/ and /ʌ/, indicating that vowel height is not conditioning this feature.

We consider that the greater nasalization present on /æ/ could play a role in contributing to its distinctiveness. Beddor [32] argues that nasal coarticulation is perceptually informative because it provides systematic and highly structured information about an upcoming nasal. In fact, nasal coarticulation is increased in certain kinds of speech where intelligibility is the primary goal and in potentially confusable words [22], suggesting that coarticulation serves as a perceptually beneficial enhancement feature. However, in the current study, while the organization of cues may indeed explain a perceptual advantage for the increased nasal coarticulation found in pre-nasal /æ/, such advantages would not directly affect the contrast between pre-nasal /æ/ and pre-nasal /ɛ/. Rather, perhaps it is the greater nasality itself in /æ/ that is distinctive relative to /ɛ/, and also relative to pre-oral /æ/. /æ/ raising results in a contextually conditioned “split” of the low front vowel phoneme with two distinct variants. In other split-æ contexts, the split can be leveraged by listeners. For example, in dialects where /æ/ raises before /g/ but not /k/, listeners are quicker to correctly disambiguate between “back” and “bag” in productions from a raised /æ/ speaker [33]. In the case of the split in the nasal system, the greater nasalization for pre-nasal /æ/ can be seen as enhancing the split.

The relationship between the pre-nasal vowel raising and the coarticulatory patterns is not arbitrary. Lowered F1 is an acoustic consequence of both raised tongue position (i.e., a raised vowel) and nasal resonances (i.e., in this case, nasal coarticulation). This acoustic relationship likely forms the basis for the sound change to begin with. Since the acoustic properties of a nasal-coarticulated vowel are ambiguous as to the gestural source of a lowered F1, listeners may reanalyze a nasalized low vowel as inherently raised in tongue position (cf., [12]). [34] report that within a speech community, speakers who produce pre-nasal /æ/ with similar lowered F1 values vary as to whether this is articulatorily realized through tongue height or, ostensibly, an increased degree of nasalization. This reanalysis and phonologization of vowel height is complete in French, where low nasal vowels have consistently higher tongue positions than corresponding oral vowels [18]. In the current study, we observe that both lowered F1 and increased nasalization appear to be phonologized on pre-nasal /æ/ in California English.

Similar to discussions from other researchers looking at secondary phonetic features used to convey phoneme contrasts (e.g., [9], [10]), the findings in the current study underscore the importance of examining vowels systems, and variation and change of phonetic systems, as multidimensional. An examination of our vowels only in terms of their F1/F2 realization would have resulted in an unclear picture, seemingly a reduction in contrast between two phonemes. Exploring other acoustic dimensions clarified the nature of the contrast between /æ/ and /ɛ/, showing that phonetic variation present in the signal can be recruited by a speech community to enhance a contrast that is reducing in distance in the primary acoustic dimension. The raising of pre-nasal /æ/, originating in coarticulatory reanalysis, threatens the /æ/-/ɛ/ distinction. The use of secondary phonetic cues, duration, formant movement, and degree of nasality, compensates for the reduction in formant space distance. Future work can assess the relative roles of these features as cues to the distinction between /æ/ and /ɛ/ in this vowel system.

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