

# Covert URs: evidence from nasalization in Panjabi

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## Abstract

Panjabi is an Indo-Aryan language spoken primarily in the Punjab province of Pakistan and the Indian state of Punjab. Long vowels contrast in nasality in the language, but this contrast is neutralized before nasal consonants:  $[\tilde{V}\tilde{V}N]$ ,  $*[VVN]$ . This paper presents air pressure data from Pakistani Panjabi showing that predictably nasal vowels before nasal consonants in the language,  $[\tilde{V}\tilde{V}N]$ , are statistically equivalent in nasality to contrastive nasal vowels,  $/\tilde{V}\tilde{V}/$  (Exp. 1). However, predictable  $[\tilde{V}\tilde{V}N]$  and contrastive nasal  $/\tilde{V}\tilde{V}/$  vowels behave differently in their interaction with a nasal harmony process, in that only contrastive nasal  $/\tilde{V}\tilde{V}/$  vowels trigger nasal harmony (Exp. 2). This difference in phonological behavior can be straightforwardly analyzed by assuming (i) that pre-nasal vowels are underlyingly oral, even in morphemes which never show alternations in nasality, and (ii) that only underlyingly nasal vowels trigger harmony. These findings support a view of phonology in which abstract underlying representations (URs) can be completely covert, never surfacing in any allomorph without some kind of symbolic alteration. Surface-oriented approaches to phonology which reject covert URs — including usage-based models relying exclusively on observed exemplars to form lexical representations — have difficulty accounting for these facts.

## 1 Introduction

Since Halle (1959) and Chomsky and Halle (1968), research in generative phonology has traditionally assumed that words and other lexical items are encoded as relatively abstract underlying representations. These *Underlying representations* (URs) are the forms stored in long-term memory that underlie all potential surface realizations of a morpheme or word. URs contain, at a minimum, any unpredictable aspects of the pronunciation of each morpheme or word; in particular, the basic phonemes which compose each morpheme. This information must be memorized as an unpredictable property of the associated morpheme or lexical item. Chomsky and Halle (1968, Ch. 8) propose that URs contain *only* this information: they are the stored form of a lexical item after all predictable phonological and phonetic detail is stripped away (cf. Prince and Smolensky 2004, Ch. 9). The UR for an English word like ‘price’  $[p^h\text{ɹ}aɪs]$  would thus be  $/p\text{ɹ}aɪs/$ , a sparse, redundancy-free, minimal specification of only those unpredictable aspects of the phonology and phonetics of ‘price’ which must be memorized.

In contrast to the sparse, redundancy-free, and phonetically abstract underlying representations encountered in traditional/classical generative phonology, a broad body of experimental literature has provided evidence suggesting that lexical representations may, in fact, include phonetically-detailed, predictable, and context-dependent information about the pronunciation of words and

morphemes (e.g. Bybee 2001; Goldrick and Cole 2023; Johnson 1997, 2006; Pierrehumbert 2001, 2016, and references therein). For example, a classic study by Goldinger (1998) explored the roles of talker familiarity and word frequency in a shadowing task and found that participants were faster to repeat words out loud if they had already heard that word previously uttered by the same speaker. He took this result as evidence that words are stored in memory as sets of *exemplars*, corresponding to phonetically-detailed traces of past experiences hearing each word, with details about speaker identity indexed to those speech memories.

Goldinger also found that speakers' own productions sometimes imitated fine-grained phonetic properties of the prompts they heard. Imitation effects were stronger with low-frequency words than high-frequency words. Goldinger proposed that this effect can be explained if speech production targets are determined by some form of averaging over the stored exemplars for each word. Such averaging predicts that imitation effects should be more evident for low-frequency words: since low-frequency words have fewer stored exemplars in memory, any single exemplar should have a relatively outsized influence on how that word is pronounced. High-frequency words, on the other hand, have many stored exemplars and so should have relatively stable production targets and be less liable to influence from recently heard productions than low-frequency words.

The preceding discussion provides only a small sample of the evidence which has been taken to support the existence of phonetically-detailed exemplar representations for words and morphemes. For a fuller picture, see e.g. Goldrick and Cole (2023); Pierrehumbert (2016) and research cited therein. Models of lexical representation which assume phonetically-detailed, stored exemplars are sometimes called *usage-based* models, because lexical representations correspond in a fairly direct way to actual, physical experiences with words and other linguistics structures.

Despite their reliance on phonetically-detailed memory traces, exemplar models are not inconsistent with abstract representations. Such abstractions act as symbolic structures not directly tethered to the physical realization of individual tokens. Instead, they serve as more abstract categories within which exemplar tokens can be classified, thereby supporting higher-order generalizations across tokens with distinct phonetic exponents (e.g. Goldinger 1998; Goldrick and Cole 2023). Indeed, it has been argued that abstract phonemes and abstract lexical representations are needed to account for patterns of sound change and phonological productivity (e.g. Pierrehumbert 2016), for constraining variation within sound categories (Wedel, 2012), for modeling spoken word recognition and phonological priming effects (e.g. Cornell et al. 2011; Ernestus 2014; Farris-Trimble and Tessier 2019; Gaskell and Marslen-Wilson 1996; Jongman 2004; Lahiri 2012; Lahiri and Marslen-Wilson 1991; Lahiri and Reetz 2010; LoCasto and Connine 2002; White et al. 2024), and for understanding phonological aphasia (e.g. Buchwald and Miozzo 2011; Goldrick and Rapp 2007), among various other experimental results (see also Krämer 2012). And of course, abstract lexical representations are justified to the extent that they are needed to model phonological alternations, phonotactics, and patterns of phonological generalization within individual languages (e.g. Hyman 2018; Kenstowicz and Kisseberth 1979; McCarthy 2007). These findings are largely compatible with the storage of phonetically-detailed episodic exemplars, provided that some type of abstract lexical representation is assumed to co-exist alongside them.

We thus assume that both abstract and exemplar representations are needed for a full understanding of how words, morphemes, and sounds patterns are learned, and ultimately stored in the mind. A number of questions then arise. How abstract may lexical representations be? How far may they diverge from actual, observed surface forms? And how do language learners generate abstract, stored representations on the basis of the surface forms that they actually hear and produce?

In traditional generative frameworks, it is perfectly acceptable — and in some sense the norm — for stored lexical forms (URs) to differ extensively from surface forms (SRs) (e.g. Kenstowicz and Kisseberth 1979). As noted above for the classical generative analysis of a word like English [p<sup>h</sup>.ɪ.əɪs] ‘price’, a redundancy-free underlying representation strips all contextually predictable detail from the representation, resulting in a UR like /p.ɪ.əɪs/.

However, there is no real empirical reason to assume that [SR] ≠ /UR/ when forms are non-alternating. Even in cases of alternation, many flavors of generative theory assume that a UR is equivalent to one of its surface alternations, as in the single surface base hypothesis (Albright, 2002) and Lexicon Optimization (Prince and Smolensky, 2004). In line with this, we assume that the substance of a UR may contain redundant information, such that the UR for ‘price’ could take a form similar to /p<sup>h</sup>.ɪ.əɪs/. However, if evidence suggests to the learner that a UR deviates from its surface exponents, more abstract representations can be acquired.

More specifically, in this paper we take the position that an underlying representation can be *completely covert*, with some properties that never appear in *any* surface form or allomorph of that UR. For example, O’Hara (2017) discusses a stem-final [i]~[Ø] alternation in Klamath, illustrated by forms like [ʔe:ɰ-a] ‘is deep’ ~ [ʔe:ɰi-tk<sup>h</sup>] ‘deep’. The two potential concrete URs for this verb stem include a consonant-final stem (/ʔe:ɰ-/) with [i]-epenthesis before the /-tk<sup>h</sup>/ suffix or an i-final stem (/ʔe:ɰi-/) with /i/-deletion before /-a/.

O’Hara argues that this stem-final [i]~[Ø] alternation cannot be analyzed as the deletion of [i] when followed by /-a/ because the suffix vowel is what typically deletes when the stem-final vowel is transparently /i/: /stupɰi-a/ → [stupɰi] ‘is a widower’. Moreover, the pattern cannot be explained by [i]-insertion for a number of reasons, one of which being that [a] is the standard epenthetic vowel in Klamath. As such it would be difficult to explain why this class of verbs idiosyncratically epenthesizes [i] instead.

Instead, O’Hara proposes that stems like [ʔe:ɰ(i)-] contain an underlying final /e/, e.g. /ʔe:ɰe/. Stem-final /e/ deletes outside of initial syllables (as in [ʔe:ɰa] ‘is deep’), and raises to [i] when deletion would produce an illicit consonant cluster (as in [ʔe:ɰitk<sup>h</sup>] ‘deep’). As a consequence of this analysis, the underlying forms of stems like /ʔe:ɰe/ are *covert*: they contain a segment, /e/, which never appears as such, unaltered, in any surface allomorph (echoing a long line of analyses of ‘yer’ vowels in Slavic languages, e.g. Gouskova 2012). The URs we describe as ‘covert’ have typically been called ‘abstract’ (e.g. Albright 2002; Hyman 2018; Kenstowicz and Kisseberth 1979; Krämer 2012; O’Hara 2017; Wang and Hayes 2025). We opt for the term ‘covert’ here to specify more precisely exactly what type of abstract representation we are concerned with: namely, an abstract representation which contain features that never surface faithfully, in any context. Analyses making use of covert representations involve a greater level of abstraction: speakers must somehow arrive at a stored lexical entry for a stem like /ʔe:ɰe/ which is qualitatively distinct from any surface form of that morpheme they have ever actually heard.

As various authors have argued, some form of ‘abstraction’ can result from statistical averaging over observed surface exemplars, as outlined above (e.g. Goldinger 1998; Goldrick and Cole 2023). However, it seems unlikely that any kind of computation over observed surface forms is sufficient, alone, to produce covert lexical representations like Klamath /ʔe:ɰe/ → [ʔe:ɰ(i)-]. To the extent that covert underlying representations like /ʔe:ɰe/ can be justified, they motivate richer, more articulated mechanisms for arriving at URs than can be produced by pooling over surface

forms.<sup>1</sup>

This paper provides phonetic and phonological evidence from Pakistani Panjabi which motivates the need for covert lexical representations. We measure oro-nasal air pressure across three different types of vowels in Panjabi: oral vowels /VV/, contrastive nasal vowels / $\tilde{V}\tilde{V}$ /, and vowels occurring before a tautomorphemic nasal consonant, pre-N /VVN/.<sup>2</sup> The results indicate that Panjabi speakers consistently produce non-alternating pre-N /VVN/ vowels with nasalization statistically equivalent to / $\tilde{V}\tilde{V}$ / vowels. The details of how we determined statistical equivalence in nasality between these two vowel types are outlined in section 3.5. In brief, statistical equivalence testing establishes a threshold where deviations between categories are considered negligible, allowing us to determine if the vowels in question fall within that range (Lakens et al., 2018; Wellek, 2010).

Nevertheless, despite statistical equivalence in nasality with contrastive nasal / $\tilde{V}\tilde{V}$ / vowels, non-alternating nasal vowels in /VVN/ interact opaquely with a pattern of nasal harmony triggered by contrastive nasal / $\tilde{V}\tilde{V}$ /. While previous Panjabi grammars offer consistent impressionistic descriptions of nasal harmony triggered by nasal vowels (e.g., Bashir and Connors 2019; Bhatia 1993), it is unclear from these descriptions whether pre-N /VVN/ vowels also trigger harmony. Our findings in this paper (section 4.2) demonstrate that they do not. For this reason, we argue that /VVN/ vowels should be analyzed as underlyingly oral, even though the vowels in question are non-alternating, and thus *always* phonetically nasal on the surface. Unless otherwise noted, all pre-N /VVN/ vowels in our experiments are non-alternating, such that the vowel never occurs without the following nasal consonant. However, there are forms in Panjabi in which a /VVN/ sequence straddles a morpheme boundary (e.g., /k<sup>h</sup>aa/ ‘eat-IMP’ vs. /k<sup>h</sup>aa-ŋ/ ‘eating’). In these cases alternations provide evidence for the underlying status of the vowel. See section 5.1 for further discussion of these forms. Phonological opacity is crucial to our argumentation here: as already observed by Ettlinger (2008) and others, productive, general patterns of opacity are often difficult to model without the assumption of URs that are *categorically* distinct from any single SR, or averaged set of SRs (see McCarthy 2007 for related discussion).

Criticisms of abstract underlying representations have also come from within the tradition of generative phonology. It has been proposed that the core functions of underlying representations — in particular, their role in determining unpredictable patterns of alternation across paradigms (Kenstowicz and Kisseberth, 1979; McCarthy, 2007) — can be subsumed by surface-oriented generalizations, including surface-to-surface relationships between allomorphs of the same morpheme (e.g. Albright 2002; Allen and Becker 2015; Burzio 1996; Cole and Hualde 2011; Hayes 1999; Scobbie et al. 1996, and various others). The pattern of opacity we discuss here, however, cannot be straightforwardly modeled through the use of surface correspondence, because the key forms (derived /VVN/ → [ $\tilde{V}\tilde{V}$ N]) are *morphologically simple*, and *non-alternating*: they have only a single surface form, and thus no possibility for producing opacity through relations between distinct surface forms (e.g. Benua 2000; Mascaró 2016; McCarthy 2005a). To the extent that surface-oriented approaches *can* account for the Panjabi data, they do so by implementing a formal distinction between predictable vs. unpredictable phonetic detail, thus recapitulating a core func-

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<sup>1</sup>Kenstowicz and Kisseberth (1977, ch.1) discuss a range of possible restrictions on representational abstraction, from highly restrictive views permitting only a single potential UR to much less constrained approaches. They argue that no absolute limits on underlying representations can be maintained. See also Wang and Hayes (2025) and Paramore (2026b) for recent treatments on the need (or lack thereof) for constraining abstraction through the lens of learnability.

<sup>2</sup>We transcribe long vowels with [VV] throughout the manuscript instead of [V:]. This transcription practice follows the general tradition of research on Indo-Aryan languages and has no bearing on our analysis.

tion of abstract URs (e.g. Cole and Kisseberth 1994, 1995). More to the point, we also argue that such approaches ultimately require the same covert underlying representations, /VVN/ → [ṼṼN], that we assume here.

Together, the Panjabi facts presented in this paper motivate a broader conclusion about the nature of phonological representations. While the discussion above has highlighted debates internal to both exemplar-based and generative traditions, the empirical issue at stake is not specific to any one framework. Instead, the results bear on a shared assumption of all *surface-oriented models*, whether eliminativist exemplar approaches or generative theories that restrict URs to surface-attested material: the assertion that lexical representations cannot contain covert structure. We argue that the Panjabi opacity pattern requires precisely the opposite, a stored lexical representation that diverges categorically from any of its surface realizations.

## 2 Panjabi

Panjabi (alternatively spelled Punjabi) is an Indo-Aryan language spoken by more than 100 million people worldwide (Hussain et al. 2019). Most Panjabi speakers live in Pakistan (78 million), where Panjabi is by far the most widely spoken first language. Additionally, the Indian states of Punjab, Haryana, and Himachal Pradesh are home to about a quarter of the total native Panjabi speakers (33 million) (Bashir and Connors 2019). Panjabi is considered to possess a high degree of dialectal diversity, with the varieties spoken in Pakistan often grouped together and termed Western Panjabi, and the varieties spoken in India termed Eastern Panjabi. Linguistic studies exploring Panjabi have largely focused on Eastern dialects, but a few descriptions of Pakistani varieties have been published in recent years (e.g., Baart 2014; Hussain et al. 2019). The data used in this study focuses on Panjabi as spoken in Pakistan. As of the summer of 2023, all 36 speakers who participated in the two experiments described here live in one of the twin cities of Pakistan, Rawalpindi and Islamabad. A significant number (56%) were born within 25 miles of the twin cities, with the rest scattered throughout the Pakistani Punjab province, in and around the areas of Gujrat and Sialkot (19%), Faisalabad (14%), Lahore (6%), and Multan (5%). Though Western Panjabi dialects vary widely from town to town, apart from the two speakers from Lahore, the nasalization results from the present study displayed a remarkable uniformity across speakers.

The Panjabi vowel inventory is provided in Figure 1. As is evident, all long vowels contrast in nasality.

|      |       | Front |      |       | Central |      |       | Back  |      |       |
|------|-------|-------|------|-------|---------|------|-------|-------|------|-------|
|      |       | short | long | nasal | short   | long | nasal | short | long | nasal |
| High | tense |       | ii   | ĩĩ    |         |      |       |       | uu   | ũũ    |
|      | lax   | ɪ     |      |       |         |      |       | ʊ     |      |       |
| Mid  | tense |       | ee   | ẽẽ    |         |      |       |       | oo   | õõ    |
|      | lax   |       | ɛɛ   | ẽẽ    | ə       |      |       |       | ɔɔ   | õõ    |
| Low  | tense |       |      |       |         |      |       |       |      |       |
|      | lax   |       |      |       |         |      |       |       | ɑɑ   | ãã    |

Figure 1: The Panjabi vowel inventory (Shackle 2003)

However, Bashir and Connors (2019, p.45) note that this contrast is confined to morpheme-final syllables, as shown in (1).<sup>3</sup>

(1) Contrastive vowel nasality in Panjabi

- |    |          |           |     |           |                 |
|----|----------|-----------|-----|-----------|-----------------|
| a. | [taa]    | ‘fever’   | vs. | [tãã]     | ‘that; so that’ |
| b. | [seek]   | ‘warmth’  | vs. | [sëëk]    | ‘termite’       |
| c. | [paavee] | ‘cot leg’ | vs. | [tʃããvëë] | ‘pumicestone’   |

Crucially, a coda nasal consonant neutralizes the vowel nasality contrast such that no minimal pairs of the shape [CVVN]-[C $\tilde{V}$  $\tilde{V}$ N] exist. This neutralization likely arises because all [V(V)N] vowels are said to be characterized by a high degree of nasality (hence [tãã] ‘melody’ is attested, but hypothetical \*[taan] is not). VN forms with a short vowel preceding a nasal consonant do exist (e.g., [ãmb] ‘mango’). Impressionistically, these are nasalized in the same manner as /VVN/ forms.

This account is supported by the results of Zahid and Hussain (2012), who conducted an acoustic study of vowel nasality in Pakistani Panjabi. While their study consisted of only three speakers, each uttering 12 repetitions of various short and long vowels from both nasal vowel types, Zahid and Hussain did not find a statistical difference in nasality between contrastive nasal [V $\tilde{V}$ ] vowels and pre-N [VVN] vowels in terms of their A1-P0 and A1-P1 values, measurements reported to correlate highly with nasality (Chen 1997; Styler 2017).<sup>4</sup>

In addition to the vowel nasality contrast and the neutralization of this contrast before nasal consonants, Panjabi also employs a process of nasal harmony, in which nasality spreads leftward from a nasal vowel, targeting all glides (/j/ and /v/) and vowels (short or long). Intervening non-glide consonants block the spread. For example, words with a stem-final oral vowel (e.g., [saa] ‘breath.sg’ and [matʃii] ‘fish.sg’) undergo nasal harmony when followed by the nasal plural suffix, /-ãã/, as shown in (2a-b).<sup>5</sup> Harmony also targets short vowels within individual morphemes, as in (2c). However, when a non-glide consonant intervenes between the stem-final oral vowel and the plural suffix, harmony is blocked, as in (2d). Importantly, descriptions of the nasal harmony process do not clarify whether the pre-N [V $\tilde{V}$ N] vowel in (2e-f)<sup>6</sup> also instigates the spread of

<sup>3</sup>As discussed below, nasalization on the penultimate vowel and glide in ‘pumicestone’ arises from a nasal harmony process.

<sup>4</sup>A1 refers to the amplitude of the highest harmonic in the first formant, which is typically dampened during the production of nasal vowels. P0 and P1, on the other hand, refer to the amplitude of low-frequency (~250-450Hz) and mid-frequency (~790-1100Hz) ‘nasal poles’ respectively. These nasal poles are additional resonances that arise from the coupling of the nasal and oral cavities during the production of a nasal vowel. Accordingly, A1-P0 and A1-P1 serve as acoustic measures of these nasality resonances. By subtracting P0 and P1 from A1 in these two equations, the measurement is normalized to control for variation in utterance intensity and/or recording conditions. By using two acoustic values that inversely correlate with nasality, these two equations provide added immunity to variations in raw energy changes across the entire spectrum (see Styler 2017 for a detailed explication of these two acoustic measures with examples).

<sup>5</sup>A glide is epenthesized intervocally in these cases to avoid vowel hiatus. An alternative analysis, in which the plural marker is underlyingly /-vãã/ and the glide deletes after stops, is ruled out because stop-glide clusters are independently licit (e.g., [taakətvər] ‘powerful’, from /taakət/ ‘power’ and /-vər/ ‘possessing’). Note also that the lack of harmony in (2d-e) vs. (2a-c) does not reflect a ‘true’ vs. ‘false’ glide distinction, since harmony applies in our data in forms with an unambiguous segmental glide followed by a contrastive nasal vowel: /tiivũ/ → [tiivũ] ‘wife’.

<sup>6</sup>We omit the underlying representations of these pre-N forms here because the following experiments aim to investigate them.

nasality, which serves as the central question of the second experiment discussed in the present work (section 4).<sup>7</sup>

(2) Nasal harmony in Panjabi (Bashir and Connors, 2019; Bhatia, 1993)

- |    |             |   |                     |                  |
|----|-------------|---|---------------------|------------------|
| a. | /saɑ-ãã/    | → | [sããũãã]            | ‘breath-PL’      |
| b. | /matʃii-ãã/ | → | [matʃiĩãã]          | ‘fish-PL’        |
| c. | /vəŋd-ivãã/ | → | [vəŋdĩvãã]          | ‘division-ADJZ’  |
| d. | /ʃaak-ãã/   | → | [ʃaaxãã]            | ‘branch-PL’      |
| e. |             |   | [ããũããm]/[aavããm]?  | ‘general public’ |
| f. |             |   | [sĩĩããŋ]/[siijããŋ]? | ‘recognition’    |

There are two possibilities with regard to the participation of [ĩĩN] vowels in nasal harmony. First, and perhaps most straightforwardly, if predictably nasal [ĩĩN] vowels are indeed statistically equivalent in nasality to contrastive nasal /ĩĩ/ vowels, and if nasal harmony in Panjabi is computed over surface phonetic representations, it would be logical to assume that both vowel types instigate the nasal harmony process in a similar fashion. After all, no relevant nasality difference exists on the surface that distinguishes the two vowels.

On the other hand, it is possible that, despite being statistically equivalent in nasality to contrastive nasal /ĩĩ/ vowels, non-alternating [ĩĩN] vowels do not instigate nasal harmony in the same way because they are phonologically distinct: specifically, because they are underlyingly oral, with predictable nasality provided on the surface by the phonological grammar.

This conclusion — which we argue in favor of — would support the existence of *covert URs*. Despite speakers consistently producing non-alternating [ĩĩN] vowels as categorically nasal, these vowels can be analyzed as oral in their URs /VVN/, given that nasality is predictable in this context. This distinction between underlyingly nasal /ĩĩ/ and underlyingly oral /VVN/ → [ĩĩN] can be leveraged to explain the uneven application of harmony: only underlying, contrastive nasal /ĩĩ/ is a harmony trigger. Without positing a difference in the underlying representations of contrastive nasal /ĩĩ/ vowels and non-alternating [ĩĩN] nasal vowels in (2), it is difficult to explain why the two vowel types behave differently in their interaction with leftward nasal spread.

Crucially, [ĩĩN] vowels in words like those in (2e-f) do not exhibit morphological alternations in which the vowel occurs without the following nasal consonant. This means there are no surface forms (apart from those involving harmony) which directly and transparently demonstrate that these [ĩĩN] vowels are underlyingly distinct from contrastive nasal /ĩĩ/ vowels (i.e. there are no alternations like /aavaa=m/ → [aavãã=m] vs. [aavaa=C] for these forms). As a result, the only direct, observed information speakers have regarding the nasality of pre-nasal [ĩĩN] vowels in words like ‘citizens’ and ‘recognition’ (2e-f) is that they are consistently realized as [+NAS]. Given that speakers do not have any direct surface evidence that [ĩĩN] vowels are underlyingly oral, surface-oriented models like exemplar theory lack the resources necessary to distinguish predictable pre-N vowels in [ĩĩN] from underlying contrastive nasal vowels /ĩĩ/.

<sup>7</sup>/aavaaam/ is historically complex (/aav-aaam/ ‘PL-common man’) but may not be synchronically analyzable. In any case, [ããm] is non-alternating under either morphological analysis, which is the relevant point here.

### 3 Experiment 1: How are /VVN/ vowels realized?

Experiment 1 measured the phonetic realization of Panjabi non-alternating [VṼN] vowels and compared their realization to contrastive nasal /ṼṼ/ and oral /VV/ vowels in the language. As mentioned above, Zahid and Hussain (2012) analyzed [VṼN] vowels for three Panjabi speakers and did not find a statistical difference between their realization and the realization of contrastive nasal /ṼṼ/ vowels with respect to acoustic correlates of vowel nasality. Thus, the first experiment aimed to replicate their findings using more speakers, and oro-nasal air pressure measurements rather than other properties of the acoustic signal that correlate with nasality.

#### 3.1 Participants

Twenty native Panjabi speakers participated in the study (eleven men and nine women) ranging in age from 22-79 ( $\bar{x}$  = 39.7; median = 33.5). All participants reported using Panjabi frequently throughout their daily lives in home, social, and academic settings. Participants were literate in Shahmukhi, a Persio-Arabic script used by most Western Panjabi speakers. Besides Panjabi, all participants also spoke Urdu, the national language of Pakistan, and many were fluent in English. While almost all participants currently reside in Rawalpindi or Islamabad as of this writing, the cities in which they grew up span the Punjab Province. Ten speakers grew up in and around Rawalpindi, four in Gujrat, two in Sialkot, one in Sargodha, two near Toba Tek Singh, and one in the far south of Punjab in Sadiqabad. Despite the expansive distances between the hometowns of the participants, the results for Experiment 1 were strikingly consistent across speakers.

#### 3.2 Stimuli and Design

Stimuli consisted of 63 monosyllabic tokens separated into three conditions: oral /VV/ (CVV), contrastive nasal /ṼṼ/ (C̃ṼṼ), and pre-N [VṼN] (CVVN). A sample of words from each condition is given in (3). The complete list of tokens is given in Table A1 of the Appendix. Pakistani Panjabi speakers use the Shahmukhi orthography — a Perso-Arabic script — for writing and reading the language. Nasal consonants are written with discrete symbols (ڳ /m/, ن /n/, ڻ /ɳ/). Long vowels also have their own symbols, but glides in Shahmukhi share the grapheme of their corresponding vowel. For example, ڳ may represent /j/ or /i:/ and ڻ may represent /v/, /u:/, /o:/, or /ɔ:/ . In addition, Shahmukhi is a partial abjad, such that short vowels are generally not indicated in the writing system. Finally, nasality on long vowels is indicated with a *nun gunnah* ڻ, which is a similar character to the Shahmukhi /n/ ن, but without the *nuqta*, or dot. However, the distinction in orthography between /n/ and nasality on vowels collapses when the nasal vowel is not the word final segment; in these cases, the *nun gunnah* is written with a *nun*, making it indistinguishable from /n/ in the orthography when not word-final, as shown for the nasal vowel in ‘swing’ in (3).

(3) Experiment 1 Conditions

| oral CVV (26)                   | contrastive nasal C̃ṼṼ (20)          | pre-N CVVN (17)                         |
|---------------------------------|----------------------------------------|-----------------------------------------|
| تھا t <sup>h</sup> ɑɑ ‘COP.PST’ | تھاں t <sup>h</sup> ɑ̃ɑ̃ ‘place, room’ | تھان t <sup>h</sup> ɑɑn ‘bolt of cloth’ |
| سو sɔɔ ‘hundred’                | سوں sɔ̃ɔ̃ ‘sleep.IMP’                  | سوں sɔɔɳ ‘rainy season’                 |
| بی bii ‘seed’                   | پینگ pīŋg ‘swing’                      | بین biin ‘musical instrument’           |

Tokens from the CVV condition were used to establish a baseline measurement of orality, so no nasal segments were included in these forms. Tokens from the  $\tilde{V}\tilde{V}$  condition had contrastive nasal  $/\tilde{V}\tilde{V}/$  vowels and served as a baseline for nasality; to avoid any coarticulatory effects, nasal consonants were excluded from all tokens in this condition. Finally, the CVVN condition consisted of monomorphemic tokens, all with a nasal coda. Nasal onsets were also excluded from this condition to avoid the effects of carryover coarticulation.

Whereas the oral CVV and contrastive nasal  $\tilde{V}\tilde{V}$  conditions provide clear baselines of orality and nasality, the CVVN condition allows for a comparison between the realization of  $[\tilde{V}\tilde{V}N]$  vowels and the other two conditions. Whenever possible, near-minimal pairs or triplets across the three conditions were used.

As is well known, differences in vowel height correlate with differences in nasality (Bell-Berti 1993; Delvaux et al. 2008; Henderson 1984). To control for this, a balanced range of vowel qualities was included in each condition as well, as shown by the contingency table in (4).

(4) Distribution of vowel quality across conditions in Experiment 1

|               |    | Condition |                                     |          | Total Items |
|---------------|----|-----------|-------------------------------------|----------|-------------|
|               |    | Oral VV   | Contrast. Nas. $\tilde{V}\tilde{V}$ | pre-N VV |             |
| Vowel Quality | ii | 4         | 1                                   | 2        | 7           |
|               | uu | 4         | 5                                   | 3        | 10          |
|               | ee | 2         | 1                                   | 0        | 3           |
|               | oo | 4         | 3                                   | 2        | 9           |
|               | ɔɔ | 2         | 1                                   | 2        | 5           |
|               | ɑɑ | 10        | 9                                   | 8        | 27          |
| Total Items   |    | 26        | 20                                  | 17       | 63          |

### 3.3 Procedure

All participants were recorded individually in a sound-attenuated room at a university in Rawalpindi, Pakistan. A native Panjabi research consultant — Amir Adkuokhar — provided participants with a consent form in Panjabi detailing what the experiment involved. They were told that the experiment measured air pressure variations from the nose and mouth to study the Panjabi sound system.

After signing the consent form and filling out a demographic questionnaire, the research consultant introduced participants to the equipment and experimental procedure. All instructions were given in Panjabi. A dual chamber oro-nasal air-pressure mask connected to two separate transducers produced by Glottal Enterprises<sup>8</sup> was used to measure air pressure from the nose and mouth during speech at a sampling rate of 11,025 Hz using Audacity. The silicone mask was constructed with a bifurcation to separate the oral and nasal chambers, allowing for simultaneous, time-aligned air-pressure measurements in each channel. These signals were used to compute changes in nasalance over time, defined as the ratio of nasal air pressure ( $A^n$ ) to the total amount of oral ( $A^o$ ) and nasal air pressure across both chambers:  $\frac{A^n}{A^n + A^o}$ . The mask was also equipped with a handle which participants used to raise and lower the mask to and from their face during the recording. Before the recording began, participants completed a test trial, in which they uttered

<sup>8</sup>Specifications for the product can be found at [https://www.glottal.com/Oro\\_Nasal\\_Mask.html](https://www.glottal.com/Oro_Nasal_Mask.html).

several words into the mask to ensure they both understood the procedure and held the mask firmly against their face during productions to prevent airflow leakage.

At this point, the recording started, and participants were presented with the 63 monosyllabic tokens in the Shahmuki script shown on the computer screen in a randomized order using a Python Graphical User Interface. Participants were told to read each item four times while holding the mask firmly against their face: twice slowly and twice using fast/rapid speech. Speech rate was self determined by speakers. However, the first author monitored productions during the experiment, reminding speakers to maintain the target speech rate patterns if they deviated noticeably from it. The experiment included speech rate as a condition to test whether vowel duration modulates the degree of nasality on /VVN/ vowels (Solé 1992, 1995). As shown by the linear mixed-effects (lmer) model in Table 1, the intended speech rate manipulations were successful: vowels in tokens produced with instructions to speak slowly were approximately 82 milliseconds longer than those produced with instructions to speak with rapid speech.

| Predictor               | $\beta$ (ms) | 95% CI     | $t$   | $p$        |
|-------------------------|--------------|------------|-------|------------|
| Intercept (fast speech) | 205          | [186, 224] | 20.74 | < .001 *** |
| slow speech             | 82           | [72, 91]   | 17.14 | < .001 *** |

Table 1: lmer model summarizing the effect of speech rate manipulations on vowel duration:  $\text{lmer}(\text{VowelDuration} \sim \text{SPEECHRATE} + (1 + \text{SPEECHRATE}|\text{speaker}) + (1|\text{word}))$ . The inclusion of vowel quality as a fixed effect did not improve fit ( $\chi^2(5) = 2.53$ ,  $p = .77$ ), so it was excluded from the model.

Tokens were presented in the Shahmukhi script with English translations below and instructions repeated at the bottom of the screen. If a word was mispronounced, the research consultant instructed participants to repeat all four iterations of the token. Recording sessions lasted between 8 and 16 minutes.

### 3.4 Analysis

The air pressure recordings were hand-annotated with segment boundaries using Praat (Boersma and Weenink 2015). Details of the annotation procedure are outlined in section 7.2 of the Appendix.

After annotation, a Praat script iterated through the annotated files, converting the raw waveforms of the oral and nasal air pressure channels into separate intensity tracks (dB) using the *To Intensity* function in Praat. The pitch floor was set to 200 Hz, with an effective window length of 16 ms and no mean subtraction. In essence, the function initiates a moving window that slides across the waveform, squaring all values and calculating a weighted average based on the distance of each value from the center of the window. A series of R scripts then converted these intensity measures into Pascal (Pa) and normalized them to a [0,1] range. Mean nasalance values ( $\frac{A^n}{A^n + A^o}$ ) were then extracted over 11 time-normalized windows for each segment (e.g., partitioning a 110 ms vowel into eleven consecutive 10 ms bins). The values were then saved in a data frame for subsequent analysis.

The oral and nasal amplitudes used to compute nasalance in all nasalance trajectory plots throughout the paper were measured in linear pressure units (Pa). Nasalance was calculated

directly from these oral and nasal pressure amplitudes. All statistical models were conducted on mean values over each time interval extracted using Praat's "get mean" function.

### 3.5 Results

Data from nineteen of the twenty speakers that participated in the experiment is included in the results presented here, summing up to 4,761 tokens (63 tokens x 4 repetitions x 19 speakers - 27 low-quality tokens) in the analysis. One speaker, MA0, was removed from the analysis because they produced a large number of tokens in which vowels from the C $\tilde{V}\tilde{V}$  and CVVN conditions exhibited abnormally low nasalance, essentially the same as vowels in the oral CVV condition.

Tokens were analyzed using R (RCoreTeam 2016). To visually compare the relative nasality between the three conditions, the vowel segment was extracted from each token, and nasalance – defined as the proportion of total air pressure present in the nasal cavity – was used to fit three generalized additive model (GAM) curves, one for each vowel type, to the data using ggplot2 (Wickham 2016). No statistical difference in nasalance was found between tokens uttered in slow speech and tokens uttered in fast speech, so speech rate was not included as a predictor in the model. This fact is evident from comparing the two low-pass filtered nasalance traces in Figure 2 for the word /biin/ 'musical instrument'. The same speaker uttered both tokens in short succession, but the words differed in speech rate; the vowel of the first repetition (#7) was 389 ms in duration, and the vowel of the second repetition (#8) was 191 ms in duration. Despite this substantial durational difference, nasalization is produced categorically across the entire span of both CVVN vowels. This indicates that the degree of nasality on the CVVN vowel is not proportionally modulated based on speech rate differences (Solé 1992, 1995).

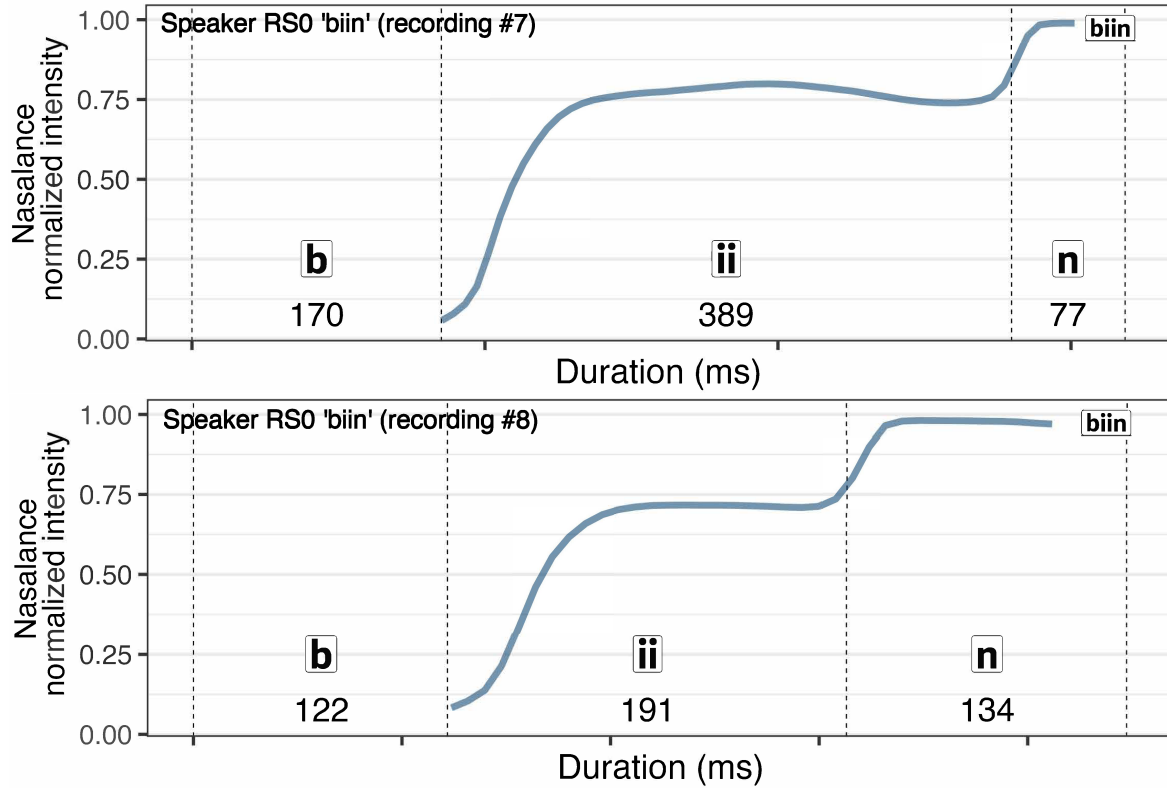


Figure 2: Nasalance traces of the word /biin/ ‘musical instrument’ uttered by the same speaker in quick succession that differ only in the speech rate. The traces show the normalized nasalance amplitude across the length of the word.

To confirm that nasalance is not modulated by speech rate for CVVN vowels, we conducted a Pearson’s correlation test to examine the relationship between the two variables. Because speech rate varies systematically across speakers, vowel durations were z-scored within speaker (i.e., each token’s duration was centered and scaled by that speaker’s mean and standard deviation). Across speakers, raw vowel durations ranged from 50 - 658 ms ( $\bar{x} = 248$ ,  $s = 74$ ), providing an ample range to evaluate rate-induced differences in nasality. The results ( $r(1290) = .09$ ,  $p < .001$  \*\*\*), visualized by the scatterplot in Figure 3, show a statistically significant positive correlation between speech rate and mean nasalance for CVVN vowels. However, Pearson correlation values less than .3 are typically regarded as *practically* insignificant, regardless of whether they reach statistical significance (Bonett, 2021, vol.2, p.3).

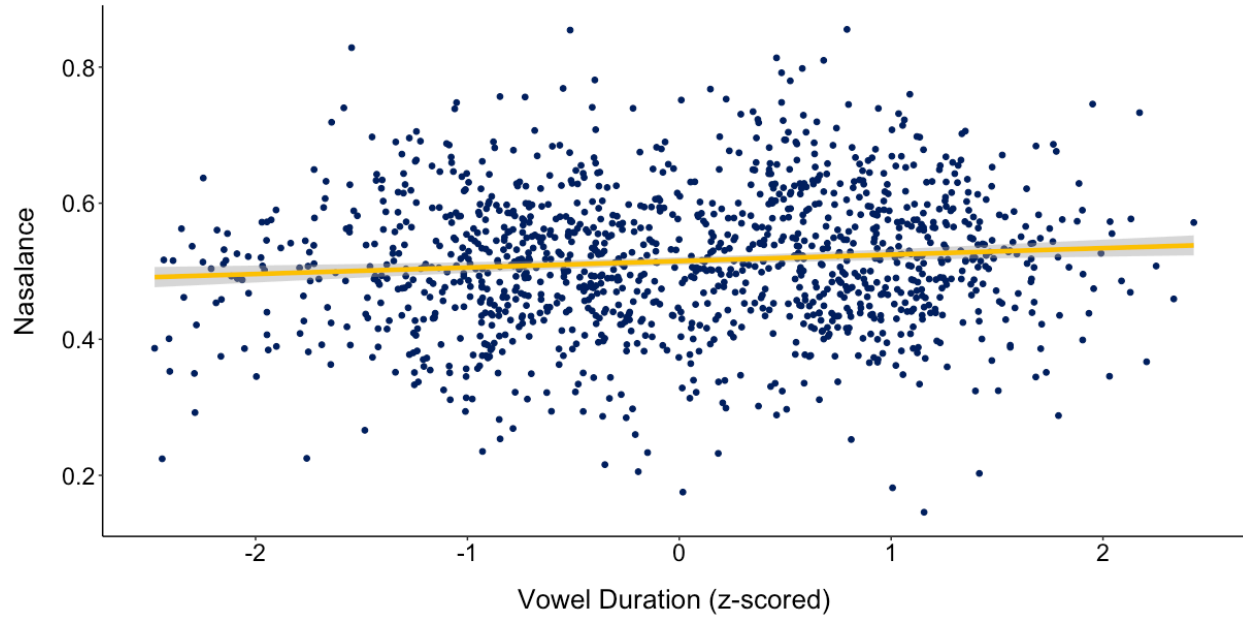


Figure 3: Scatterplot showing the .09 Pearson Correlation value between speech rate (by-speaker z-scored vowel duration) and mean nasalance for all CVVN vowels produced by nineteen speakers in Experiment 1. A correlation test using raw duration yielded similar results:  $r(1290) = .03$ ,  $p = .34$ , except that the correlation was insignificant.

Figure 4 displays plots of the three GAM curves depicting mean nasalance across all tokens and speakers. As expected, nasalance for oral CVV vowels remains steady and noticeably lower than the other two vowel types at about 20% across the length of the oral vowel. For the contrastive nasal  $C\tilde{V}\tilde{V}$  vowel condition, on the other hand, nasalance begins at about 32% at the onset of the vowel and rises steadily until reaching a plateau-like position at about 55-60% nasalance a third of the way through the vowel. This proportion of nasalance is maintained throughout the remainder of the vowel's duration. As for the nasalance of  $[\tilde{V}\tilde{V}N]$  vowels in the CVVN condition, they follow a very similar pattern to the contrastive nasal  $C\tilde{V}\tilde{V}$  vowel condition, in which nasalance at the onset of the vowel sits at approximately 32%, followed by a steady rise in nasalance until a plateau is reached at about 55-60% nasalance, which is maintained through the offset of the vowel.

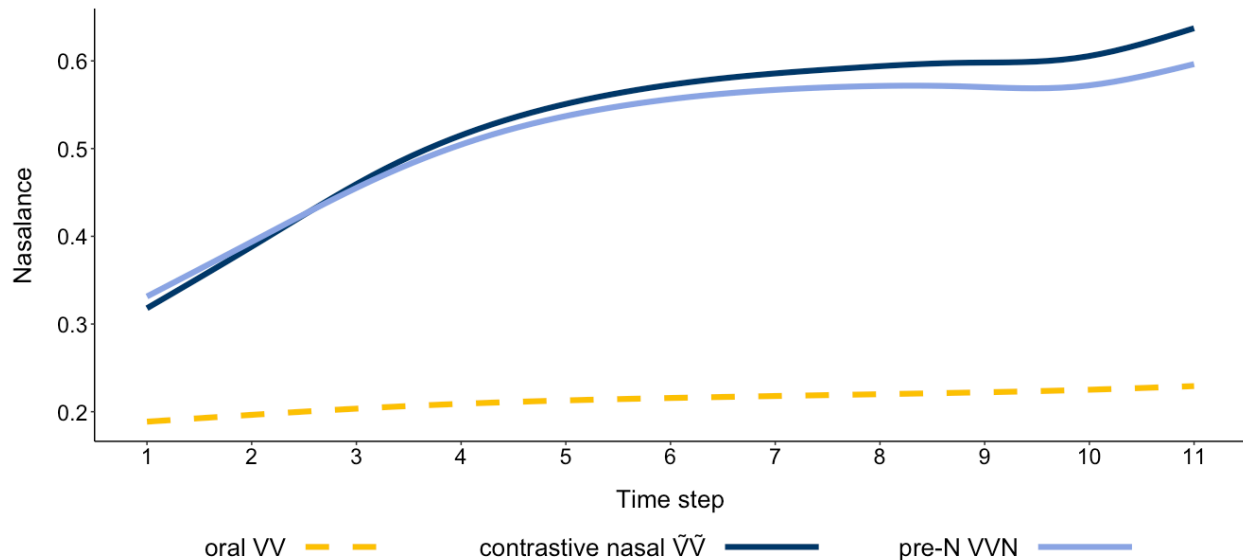


Figure 4: GAM curves separated by condition showing mean vowel nasalance across 11 normalized timesteps for all monosyllabic tokens from Experiment 1 for nineteen speakers.

To quantitatively compare the nasalance between  $\tilde{C}\tilde{V}$  and CVVN vowels, a linear mixed-effects regression (lmer) model was fit to the data using the `lmer()` function from the `lme4` package (Bates et al., 2025) with mean vowel nasalance as the dependent variable and `CONDITION` ( $\tilde{C}\tilde{V}$  and CVVN), `TIMESTEP` (beginning, middle, final), the `CONDITION*TIMESTEP` interaction, and `VOWELQUALITY` included as the four fixed effects. Oral vowels were omitted as an additional level of `CONDITION` in the model to allow for a more straightforward comparison between CVVN and  $\tilde{C}\tilde{V}$  vowels. Moreover, rather than include all eleven steps at which nasalance was measured as separate levels of the `TIMESTEP` factor, the steps were binned into three different levels, with steps 1-4 recoded as the first 1/3 of the vowel, steps 5-8 recoded as the second 1/3, and steps 9-11 recoded as the final 1/3. `VOWELQUALITY` was included as a predictor to account for the known differences in nasality across different vowel qualities mentioned above. A likelihood ratio test showed that the addition of `VOWELQUALITY` as a fixed effect significantly improved the fit ( $\chi^2(5) = 28.83, p < .001^{***}$ ), so it was retained in the model. By-word random intercepts were included, as were by-speaker random intercepts and random slopes for `CONDITION`. In addition, a likelihood ratio test comparing the complex model with a model that dropped the main effect of `CONDITION`, the `CONDITION*TIMESTEP` interaction, and by-speaker random intercepts and random slopes for `CONDITION` showed that the complex model had a significantly better fit:  $\chi^2(5) = 488.16, p < .001^{***}$ . This difference is likely due to the interaction effects discussed below.

The results of the lmer model are provided in Table 2. The main effects of `TIMESTEP` and `VOWELQUALITY` were effect (aka sum) coded, and the main effect of `CONDITION` was dummy (aka treatment) coded. Consequently, the intercept of the model ( $\beta_0$ ) refers to the mean nasalance of contrastive nasal  $\tilde{C}\tilde{V}$  vowels, averaged across all levels of the `TIMESTEP` and `VOWELQUALITY` factors. The CVVN coefficient ( $\beta_1$ ) is the value of primary interest in the model, quantifying the estimated difference between the two vowel types. The coefficients for `TIMESTEP` and `VOWELQUALITY`— $\beta_2$ - $\beta_{10}$  in Table 2—represent deviations of the listed factor level from the average nasalance of contrastive nasal  $\tilde{C}\tilde{V}$  vowels, controlling for the other predictors. The final three coefficients ( $\beta_{11}$

-  $\beta_{13}$ ) reflect the  $\text{CONDITION} \times \text{TIMESTEP}$  interaction, capturing potential differences in the temporal trajectory of nasalance between contrastive nasal  $\text{C}\tilde{\text{V}}\tilde{\text{V}}$  and CVVN vowels.

The  $\text{CONDITION} \times \text{TIMESTEP}$  interaction was significant at the beginning and end of the vowel, showing that CVVN vowels are slightly more nasalized than contrastive nasal  $\text{C}\tilde{\text{V}}\tilde{\text{V}}$  in the beginning third of the vowel and slightly less nasalized in the final third. Nevertheless, while the interaction is statistically significant, the predicted differences in nasalance at the vowel onset and offset are very small on the nasalance scale ( $\pm .017$  nasalance or 1.7% percentage differences). These localized deviations across conditions are consistent with small phonetic differences across contexts (e.g., non-identical onsets and the lack of a coda in most  $\text{C}\tilde{\text{V}}\tilde{\text{V}}$  tokens). Moreover, the large dataset provides sufficient power for the model to detect such subtle effects. Crucially, incorporating the interaction does not change the overall pattern; the two conditions exhibit highly similar nasalance trajectories across the vowel, and the main effect of condition remains substantively interpretable in light of these small timestep interactions.

Similarly, the main effect of  $\text{VOWELQUALITY}$  was significant for four of the six vowels included in the study, reaffirming that different vowels exhibit differing degrees of nasalization, controlling for other factors.

With the  $\text{CONDITION} \times \text{TIMESTEP}$  interaction and  $\text{VOWELQUALITY}$  effects noted above, the primary takeaway from the model for our purposes is located in the first two rows. Specifically, the estimated difference of .016 nasalance between the contrastive nasal  $\text{C}\tilde{\text{V}}\tilde{\text{V}}$  vowel and the pre-N CVVN vowel does not reach statistical significance. This means that the null hypothesis that the two vowels are statistically equivalent in terms of their nasalance values cannot be ruled out.

| Predictor                                                | $\beta$ | 95% CI         | $t$    | $p$        |
|----------------------------------------------------------|---------|----------------|--------|------------|
| Intercept ( $\text{C}\tilde{\text{V}}\tilde{\text{V}}$ ) | .541    | [.514, .568]   | 39.55  | < .001 *** |
| CVVN                                                     | -.016   | [-.039, .007]  | -1.36  | .18        |
| Beg                                                      | -.114   | [-.117, -.112] | -91.54 | < .001 *** |
| Mid                                                      | .040    | [.038, .043]   | 32.29  | < .001 *** |
| Fin                                                      | .074    | [.071, .077]   | 51.04  | < .001 *** |
| uu                                                       | .038    | [.016, .059]   | 3.44   | .002 **    |
| ii                                                       | .052    | [.021, .082]   | 3.34   | .002 **    |
| oo                                                       | -.046   | [-.071, -.022] | -3.66  | < .001 *** |
| ɔɔ                                                       | -.009   | [-.040, .021]  | -.60   | .55        |
| ee                                                       | -.012   | [-.061, .037]  | -.47   | .64        |
| ɑɑ                                                       | -.022   | [-.04, -.004]  | -2.44  | .02 *      |
| CVVN: Beg                                                | .017    | [.013, .021]   | 9.23   | < .001 *** |
| CVVN: Mid                                                | -.002   | [-.005, .002]  | -.88   | .38        |
| CVVN: Fin                                                | -.015   | [-.019, -.011] | -7.27  | < .001 *** |

Table 2: Lmer model summarizing the effect of  $\text{CONDITION}$  ( $\text{C}\tilde{\text{V}}\tilde{\text{V}}$ , CVVN),  $\text{TIMESTEP}$  (beginning, middle, final), the  $\text{CONDITION} \times \text{TIMESTEP}$  interaction, and  $\text{VOWELQUALITY}$  (ɑɑ, ɔɔ, oo, ee, uu, ii) on mean nasalance for nineteen speakers:  $\text{Lmer}(\text{nasalance} \sim \text{CONDITION} \times \text{TIMESTEP} + \text{VOWELQUALITY} + (1 + \text{CONDITION} | \text{speaker}) + (1 | \text{word}))$ .

Importantly, while no effect of  $\text{CONDITION}$  was found to alter the mean nasalance of the two vowels, the results do not allow us to conclude that the nasalance of contrastive nasal  $\text{C}\tilde{\text{V}}\tilde{\text{V}}$  and

pre-N CVVN vowels are equivalent. To do so, an equivalence test must be conducted to determine whether we can accept the null hypothesis that the mean nasalance of the two vowel types is the same. Within the framework of classical statistics, a test of equivalence relies on determining a region of practical equivalence ( $-h$  to  $h$ ) for a specific research question and examining whether or not the confidence interval for the difference in means between two groups falls within that region (Bonett 2021; Lakens et al. 2018; Wellek 2010). If the confidence interval for the difference is wholly contained within that interval, the hypothesis that a practical difference exists between the two groups with respect to the dependent variable can be rejected. For this experiment, the dependent variable is mean nasalance, and the two groups of interest are the vowels in the C $\tilde{V}\tilde{V}$  and CVVN conditions.

To determine a region of practical equivalence (*RoPE*) for mean nasalance in Panjabi, we first grouped all contrastive nasal C $\tilde{V}\tilde{V}$  tokens from Experiment 1 by speaker and vowel quality and calculated the mean and standard deviation of segmental nasalance within these groups. Computing by-speaker nasalance means separately for each vowel quality controls for inherent differences in nasalance across vowel heights. For each speaker, the mean nasalance and standard deviation was then averaged across vowel qualities to obtain standard nasalance distributions within the contrastive nasal C $\tilde{V}\tilde{V}$  condition. Finally, the *RoPE* was defined as  $\pm 2$  standard deviations of nasalance for the speaker with the narrowest variation. Because all vowels in the contrastive nasal C $\tilde{V}\tilde{V}$  condition in this experiment are phonologically contrastive nasal vowels, any variation in nasalance of these vowels within an individual speaker can be treated as phonologically negligible. Setting the *RoPE* to capture 95% of tokens ( $\pm 2$ SDs) produced by the speaker with the strictest distribution in nasalance therefore establishes a conservative threshold below which variation can be interpreted as within-category phonetic noise, rather than a cross-category, intentional phonetic or phonological difference. Our choice of *RoPE*, then, is specified by (i) linguistic facts not connected to the sample statistic: the functional equivalence of different levels of phonetic nasality within the phonological category / $\tilde{V}\tilde{V}$ /. In addition, we choose the most conservative *RoPE* possible given (i), thus biasing the comparison **against** our conclusions. Using this method, we estimate the *RoPE* for nasalance on contrastive nasal C $\tilde{V}\tilde{V}$  vowels in Panjabi to be  $\pm .061$ .<sup>9</sup>

Figure 5 shows the proposed *RoPE* along with the nasalance data from vowels in the contrastive nasal C $\tilde{V}\tilde{V}$  condition from all speakers in Experiment 1. The yellow points on the plot represent the mean nasalance for C $\tilde{V}\tilde{V}$  vowels for each speaker from Experiment 1, with the tails indicating  $\pm$  two standard deviations (capturing 95% of productions) from that mean. Speakers are ordered from left to right by magnitude of their standard deviation in mean nasalance. When a listener normalizes expected nasalance levels for a given speaker, any nasalance value within two standard deviations of that speaker's typical nasalance level for a C $\tilde{V}\tilde{V}$  vowel can probably be safely interpreted as nasal. The magnitude of the suggested *RoPE* of  $\pm .061$  shown in blue can be interpreted in a similar way.

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<sup>9</sup>See Paramore (2026a, ch.4) for the establishment of a nasalance *RoPE* of  $\pm .075$  using fundamentally the same equipment and methods in another language, Mankiyali.

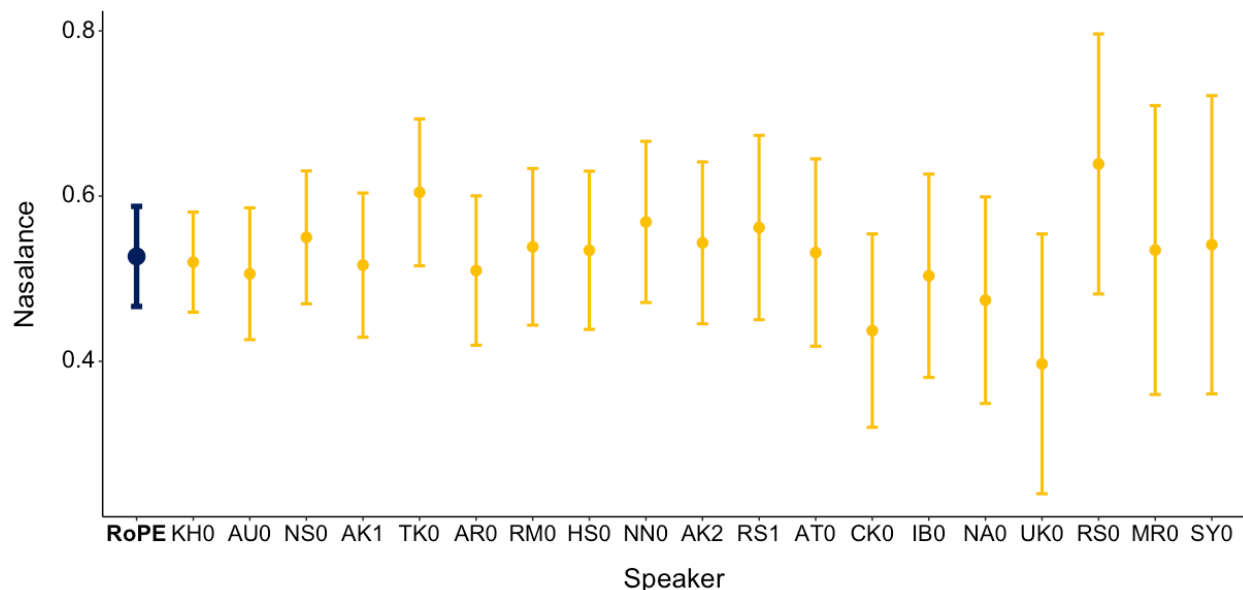


Figure 5: Dot and whisker plot showing mean nasalance of  $C\tilde{V}\tilde{V}$  vowels from Experiment 1. The yellow dots and tails represent the mean  $C\tilde{V}\tilde{V}$  vowel nasalance for each speaker and  $\pm$  two standard deviations around this mean nasalance value respectively. Speakers are ordered from left to right by magnitude of standard deviation. The blue point shows the mean nasalance across all speakers, and its tails represent the proposed *RoPE* of  $\pm 0.061$ .

Reexamining the 95% CI for the estimated difference in nasalance between pre-N CVVN and contrastive nasal  $C\tilde{V}\tilde{V}$  in row 2 of Table 2, which compares nasalance in CVVN vowels to nasalance in  $C\tilde{V}\tilde{V}$  vowels, we see that the entire confidence interval ( $[-.039, .007]$ ) falls well within the bounds of the proposed *RoPE* ( $\pm 0.061$ ). Therefore, we can conclude that the mean nasalance of the two vowel types is statistically equivalent. This allows us to assert that pre-N CVVN vowels surface as phonologically  $[+NAS]$  in the same way as contrastive nasal  $C\tilde{V}\tilde{V}$  vowels in Panjabi.

To sum up, the results of Experiment 1 confirm and extend the findings from the acoustic analysis in Zahid and Hussain (2012): pre-N  $[\tilde{V}\tilde{V}N]$  vowels are not meaningfully different from contrastive nasal  $/\tilde{V}\tilde{V}/$  vowels with respect to their phonetic nasality. Of course, it is possible that other acoustic correlates to nasality beyond nasalance might differ between these two vowels (Garellek et al., 2016; Shosted, 2015). We argue against this in section 7.3 of the Appendix.

One final note is that the discussion here assumes that, because contrastive nasal  $/\tilde{V}\tilde{V}/$  and pre-N  $[\tilde{V}\tilde{V}N]$  vowels are produced with statistically equivalent nasality, they are *perceptually* indistinguishable. Of course, the production studies in this paper cannot directly address questions about perception, so future research is therefore needed to confirm that contrastive nasal  $/\tilde{V}\tilde{V}/$  vowels are perceptually indistinguishable from pre-N  $[\tilde{V}\tilde{V}N]$  vowels to listeners. See also Beddor and Krakow (1999).

## 4 Experiment 2: Do [ĩĩN] vowels trigger nasal harmony?

Experiment 1 found that contrastive nasal /ĩĩ/ and non-alternating [ĩĩN] vowels are practically and statistically equivalent with respect to the acoustic realization of vowel nasality. Experiment 2 explores how these two vowel types interact with the phonological process in Panjabi of regressive nasal harmony. Specifically, Experiment 2 is designed to test if statistical differences exist between contrastive nasal /ĩĩ/ and non-alternating [ĩĩN] with respect to their ability to trigger nasal harmony in Panjabi.

As a reminder, previous impressionistic descriptions of Panjabi document a process of regressive nasal harmony in the language, in which nasal vowels trigger the leftward spread of nasality onto preceding glides and vowels (Bashir and Connors, 2019; Bhatia, 1993): /saɑ-āā/ → [sāāũāā] ‘breath-PL’. Non-glide consonants serve as blockers, preventing further spreading of nasality: /ʃaak-āā/ → [ʃaaxāā] ‘branch-PL’.

The results of Experiment 1 help frame two potential hypotheses regarding the interaction of surface [ĩĩN] vowels with nasal harmony. The first hypothesis asserts that, because contrastive nasal /ĩĩ/ and non-alternating [ĩĩN] vowels appear to be statistically indistinguishable in their phonetic nasality, they should *behave* identically in terms of triggering nasal harmony.

The abstract underlying representations provided by generative phonology also raise a second possibility. Vowel nasality in [ĩĩN] is predictable rather than contrastive in Panjabi. As such, surface [ĩĩN] could be analyzed as underlyingly /VVN/, with an oral vowel; predictable nasality would then be supplied by a rule or other grammatical device. This analysis produces a distinction between contrastively nasal vowels /ĩĩ/ — which would be underlyingly nasal — and underlyingly oral vowels in /VVN/.

Thus, a second hypothesis is that /ĩĩ/ and [ĩĩN] vowels might behave *differently* with respect to triggering harmony because they have a different underlying status. Specifically it could be that only underlying, contrastive nasal /ĩĩ/ triggers harmony, while underlying oral /VVN/ → [ĩĩN] does not.

Importantly, forms with contextually nasal vowels /VVN/ → [ĩĩN] in our experiments are all non-alternating (e.g., [tāān] ‘melody’ and [xũũn] ‘blood’). There is thus no surface evidence that these vowels are anything other than nasal. For this reason, hypothesis 2 is only statable in frameworks which either (i) allow for covert URs which are qualitatively distinct from any observed surface form(s), or (ii) invoke other mechanisms for distinguishing between contrastive vs. predictable vowel nasality.

In sections 5.2.1 and 5.2.2 we argue that these results are difficult to accommodate in surface-oriented models couched in either exemplar theory or generative frameworks.

### 4.1 Participants, stimuli, design, and analysis

Sixteen additional native Panjabi speakers (eleven men and five women) who did not participate in Experiment 1 took part in Experiment 2. Ages ranged from 18 to 43 ( $\bar{x}$  = 28.2; median = 27). Besides Panjabi, all participants also spoke Urdu, the national language of Pakistan, and many were fluent in English. A handful of speakers reported fluency in other languages, such as Pashto, Pothowari, Sindhi, and Turkish. All participants currently reside in Rawalpindi, but, similar to the participants from Experiment 1, their hometowns are spread across the Punjab province. Ten

speakers grew up in Rawalpindi, two in Sargodha, one in Sialkot, one in Multan, and two in Lahore.

Similar to the first experiment, stimuli were sourced from three main vowel types: oral /VV/, contrastive nasal / $\tilde{V}\tilde{V}$ /, and non-alternating pre-N [ $\tilde{V}\tilde{V}N$ ] vowels. Here, however, all words were either di- or trisyllabic, and the shape of the final two syllables was controlled for, such that every word contained a vowel–glide–vowel sequence (VGV) across the last two syllables. This construction made it possible to examine whether the three vowel types differ in their interactions with nasal harmony.

Tokens from all three vowel conditions were produced with an enclitic CV postposition beginning with an oral stop (e.g. /aavadam=də/ ‘general public=GEN’). In addition to these three conditions, words ending in a contrastive nasal / $\tilde{V}\tilde{V}$ / vowel followed by a nasal-initial NV postposition were included as an additional condition. Bashir and Connors (2019, p.244) state that, in Panjabi, grammatical postpositions immediately follow the constituent they modify, phonologically integrating with it and lacking independent stress or prosodic constituency. By including a condition in which contrastive nasal / $\tilde{V}\tilde{V}$ / vowels are immediately followed by a postposition beginning with a nasal consonant, the contextual environment of / $\tilde{V}\tilde{V}$ =NV/ more closely mimics that of [ $\tilde{V}\tilde{V}N$ ] vowels. This facilitates a more direct comparison of nasalance patterns between the two vowel types (see section 4.4 for detailed discussion).

Altogether, four distinct conditions with 6-10 tokens each were included in the experiment, as shown in Table 3. For the conditions with oral vowels and pre-N vowels, the tokens do not alternate between CV and NV postpositions. Accordingly, we omit explicit reference to the postposition in the condition labels, referring to them as oral [VGV] and pre-N [VG $\tilde{V}N$ ] respectively.

Notably, the label for the pre-N [VG $\tilde{V}N$ ] condition reflects a surface form in which the pre-N vowel is nasalized, but nasal harmony does not extend to the preceding segments. This label anticipates the results presented in section 4.2.4, where we show that nasal harmony does not apply to pre-N [VG $\tilde{V}N$ ] forms.

By contrast, for the two contrastive nasal conditions — [ $\tilde{V}\tilde{G}\tilde{V}$ =NV] and [ $\tilde{V}\tilde{G}\tilde{V}$ =CV] — we retain the enclitic in the condition labels to distinguish between them. The labels of the two contrastive nasal conditions also encode nasal harmony, in anticipation of the results in sections 4.2.2 and 4.4.

Twenty-seven filler items were also randomly dispersed throughout the token set. Complete glosses of all tokens included in the experiment are provided in Table A2 in the Appendix.

| oral [VG̃V]                 |             | pre-N [VG̃VN] |                  |
|-----------------------------|-------------|---------------|------------------|
| /sət-aajii də/              | ‘27’        | /dʒəvaan də/  | ‘a youth’        |
| /ɔɔlii-jaa də/              | ‘pious men’ | /ədʒəvɛɛn də/ | ‘omum seed’      |
| /həvaa də/                  | ‘air’       | /siijaaŋ də/  | ‘recognition’    |
| /tʃoo-vii də/               | ‘24’        | /teejaaŋ də/  | ‘attention’      |
| /paavee də/                 | ‘cot leg’   | /lɛɛ-jaaŋ də/ | ‘taking’         |
| /beevaa də/                 | ‘widow’     | /aavaam də/   | ‘general public’ |
| /dəvaa də/                  | ‘medicine’  |               |                  |
| /taavuu də/                 | ‘uncle’     |               |                  |
| /vək <sup>h</sup> aavee də/ | ‘boasting’  |               |                  |
| /mʊk <sup>h</sup> iijaa də/ | ‘chief’     |               |                  |

| contrastive nasal [ṼG̃Ṽ=NV] |               | contrastive nasal [ṼG̃Ṽ=CV] |               |
|-------------------------------|---------------|-------------------------------|---------------|
| /tʃaavēē nʊ/                  | ‘pumicestone’ | /tʃaavēē də/                  | ‘pumicestone’ |
| /uu-vēē nʊ/                   | ‘in that way’ | /uu-vēē də/                   | ‘in that way’ |
| /doo-vāā nʊ/                  | ‘both sides’  | /doo-vāā paase/               | ‘both sides’  |
| /kii-vēē nʊ/                  | ‘somehow’     | /kii-vēē də/                  | ‘somehow’     |
| /ɛɛ-vēē nʊ/                   | ‘in vain’     | /ɛɛ-vēē də/                   | ‘in vain’     |
| /matʃii-jāā nɪ/               | ‘fish-PL’     | /matʃii-jāā də/               | ‘fish-PL’     |
| /tiivii nɪ/                   | ‘woman’       | /tiivii də/                   | ‘woman’       |
| /saa-vāā nɪ/                  | ‘breaths’     | /saa-vāā də/                  | ‘breaths’     |

Table 3: Experiment 2 tokens.

Both the contrastive oral [VG̃V] and contrastive nasal [ṼG̃Ṽ=CV] conditions provide established baselines for an oral vowel with no nasality in the signal and a nasal /ṼṼ/ vowel that triggers nasal harmony, respectively. The pre-N [VG̃VN] condition, on the other hand, is the condition of interest. Importantly, VVN sequences from the pre-N [VG̃VN] condition never straddle a morpheme boundary, so Panjabi speakers lack experience with alternations that reveal the oral status of these [ṼṼN] vowels when not followed by a nasal consonant. Thus, assuming similar results to Experiment 1, in which [ṼṼN] vowels are statistically equivalent to contrastive nasal /ṼṼ/ vowels in terms of nasality, [ṼṼN] vowels in these tokens should always be realized as [+NAS].

Our primary focus here is on whether pre-N vowels in the pre-N [VG̃VN] condition trigger nasal harmony to the same extent as contrastive nasal /ṼṼ/ vowels in the [ṼG̃Ṽ=CV] condition. Section 4.2.1 discusses the apparent optionality of nasal harmony triggered by contrastive nasal /ṼṼ/ vowels. Section 4.2.2 analyzes tokens with harmony triggered by contrastive nasal /ṼṼ/ vowels. Section 4.2.4 shows that the vowels in the pre-N [VG̃VN] condition do not trigger nasal harmony, despite being as strongly nasalized as contrastive nasal /ṼṼ/ vowels in the [ṼG̃Ṽ=CV] condition (section 4.2.3).

## 4.2 Results

A total of 2,048 potential tokens (16 speakers x 4 repetitions x 32 words) resulted from the recordings. Unfortunately, the recording for one speaker (MI0) showed little to no differences between the contrastive oral [VG̃V] and contrastive nasal [ṼG̃Ṽ=CV] conditions, so the data from this participant was removed. In addition, 53 more tokens across the remaining fifteen

speakers were removed due to poor audio quality. After removing these words, a total of 1,867 tokens remained in the analysis.

All speakers in Experiment 2 produced tokens from the oral [VGV] and the contrastive nasal [ĩĩĩĩ=CV] and [ĩĩĩĩ=NV] conditions uniformly, but productions of the pre-N [VGĩĩ] condition fell into two distinct patterns that require individual attention. All fifteen speakers lacked nasal harmony across the preceding vowel-glide sequence in the pre-N [VGĩĩ] condition (section 4.2.4). Thirteen speakers categorically nasalized the [ĩĩĩĩ] vowel immediately preceding the nasal consonant (section 4.2.3). However, the remaining two speakers systematically lacked categorical nasality on all [ĩĩĩĩ] vowels, instead demonstrating a pattern of anticipatory coarticulation. We discuss these two speakers in section 7.5 of the Appendix. It is likely that these production differences arise from dialectal variation, since these two speakers were the only participants from either experiment that grew up in Lahore. As such, their data is excluded from the analysis in the main text.

### 4.2.1 Optionality of Nasal Harmony

Before examining the results in more detail, one other fact about nasal harmony in the contrastive nasal [ĩĩĩĩ=CV] and [ĩĩĩĩ=NV] conditions must be considered. Across all speakers and words in the experiment, it was evident that nasal harmony on the penultimate, pre-glide stem vowel only sometimes applied: for 41% of tokens in the contrastive nasal [ĩĩĩĩ=CV] and [ĩĩĩĩ=NV] conditions (n=371), nasal harmony was not triggered. These 371 tokens are broadly distributed across speakers and words rather than concentrated in a small subset of the data. As no grammatical descriptions known to us report optionality or variability for nasal harmony in Panjabi, this result was unexpected.

Figure 6 illustrates with two productions of /uu-uĩĩĩ də/ ‘in that way’ by speaker AA1, uttered within one second of each other. Examining the nasal channels in the figure for both productions, nasalance on the penultimate, pre-glide stem vowel exhibits categorical nasalization across the entire [VGV] sequence for recording #159 (top panel). For recording #160 (bottom panel), on the other hand, nasalance remains at the level of an oral vowel for the entirety of the pre-glide vowel’s duration and then rises rapidly at the onset of the glide.

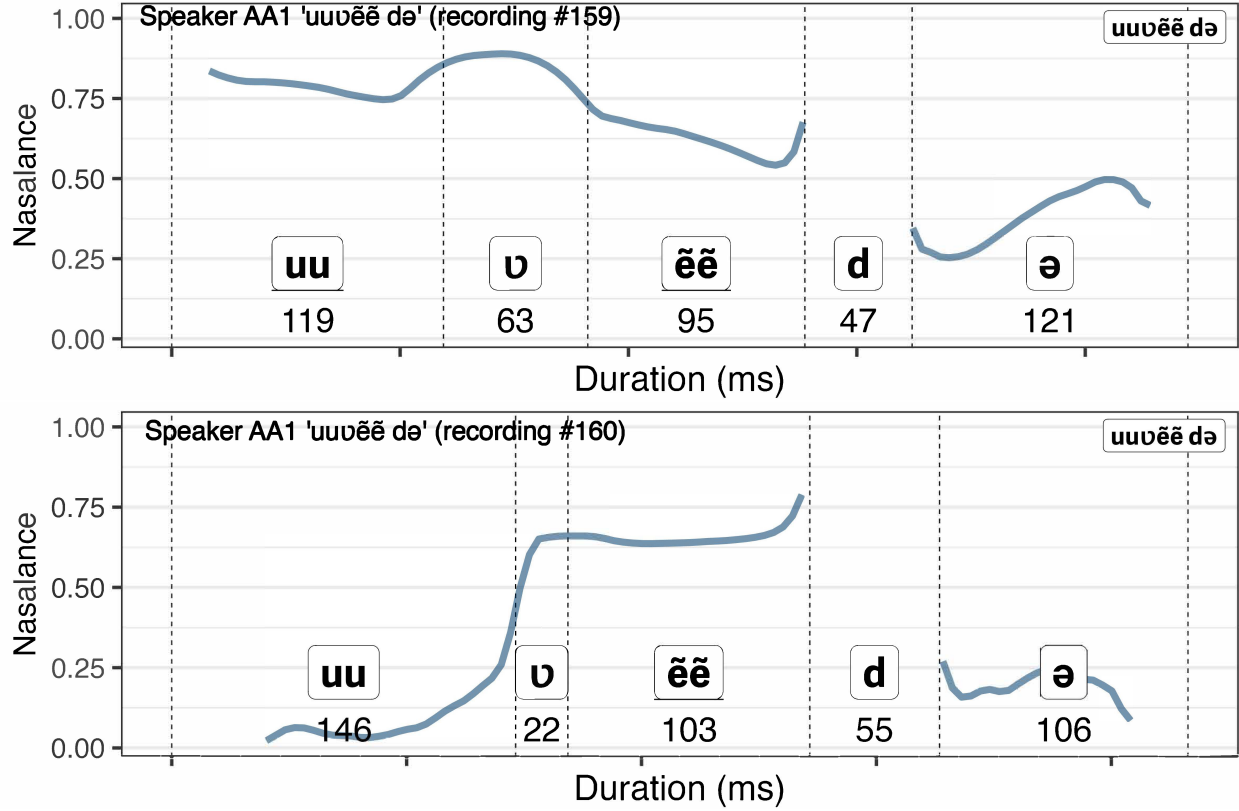


Figure 6: Nasalance traces for two different productions of /uuvẽẽ də/ ‘in that way’ by the same speaker in quick succession that differ only in the application of nasal harmony. The y-axis corresponds to nasalance, calculated in Praat by taking the normalized proportion of nasal air pressure to the total amount of air pressure in the vocal tract.

Importantly, this variable application of the nasal harmony process was present for all speakers and words in both the contrastive nasal [ṼḠṼ=CV] and [ṼḠṼ=NV] conditions. Moreover, harmony was virtually absent in the pre-N [VGṼN] condition, as we discuss below.<sup>10</sup> These observations indicate that nasal harmony in Panjabi applies optionally when triggered by /ṼṼ/.

Because Experiment 2 aims to examine whether [ṼṼN] vowels differ from contrastive nasal /ṼṼ/ vowels in their ability to trigger nasal harmony in the language, all tokens that clearly lacked harmony in the [ṼḠṼ=CV] and [ṼḠṼ=NV] conditions were removed to prevent the obfuscation of the harmony pattern. To do this objectively, a cutoff was established for each speaker at 2.5 standard deviations above the mean nasalance value of the penultimate stem vowels in the baseline oral [VGV] condition. Because this threshold encompasses the vast majority of natural baseline variance for oral vowels, any token exceeding it can be confidently classified as exhibiting genuine nasalization.

Figure 7 illustrates this application for speaker IS0. As is evident, the distribution of penultimate

<sup>10</sup>Across the dataset, a small number of tokens in the pre-N [VGṼN] condition showed unusually high nasalance across the full [VGṼN] sequence. Similarly, a few utterances in the [ṼḠṼ=CV] condition displayed a final stem vowel – an underlying, contrastive nasal vowel – that nonetheless exhibited nasalance levels characteristic of an oral vowel. Given how few tokens show these patterns, we interpret them as performance artifacts rather than the intentional implementation of a particular nasalance pattern as such.

stem vowels in the contrastive  $[\tilde{V}\tilde{G}\tilde{V}]$  conditions is bimodal: the majority of vowels exhibit a mean nasalance of approximately .65, while a smaller concentration clusters around a mean nasalance of roughly .4. The vertical line represents the strict 2.5 SD cutoff calculated for this specific speaker; tokens falling to the left of the line were removed, and tokens to the right were retained.

No tokens from the pre-N  $[\tilde{V}\tilde{G}\tilde{V}N]$  condition were removed in this process. Thus, the comparison between contrastive nasal  $[\tilde{V}\tilde{V}]$  vowels and  $[\tilde{V}\tilde{V}N]$  vowels in this study includes only those tokens in the contrastive nasal  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  and  $[\tilde{V}\tilde{G}\tilde{V}=NV]$  conditions in which the nasal harmony process *does* apply. That is, tokens like recording #160 (bottom panel) in Figure 6 above were removed.

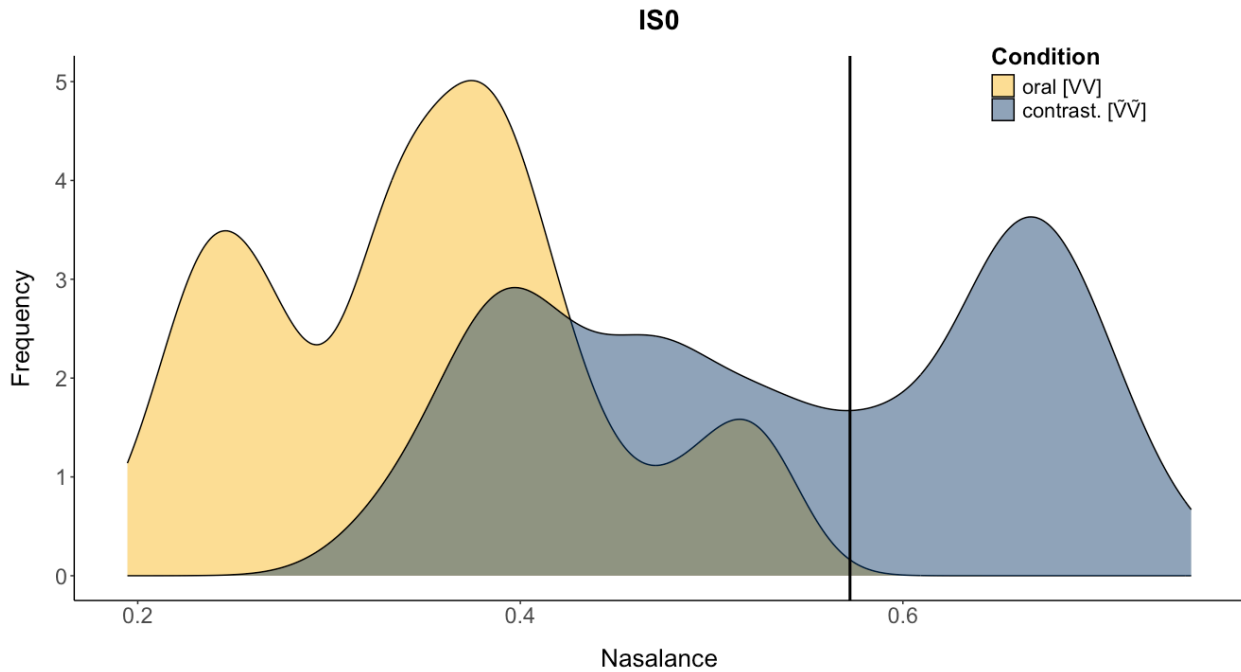


Figure 7: Density plot showing the distribution of mean nasalance for penultimate pre-glide stem vowels for speaker IS0. Contrastive nasal  $[\tilde{V}\tilde{V}]$  includes penultimate stem vowels from both the  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  and  $[\tilde{V}\tilde{G}\tilde{V}=NV]$  conditions. The multimodal distribution in the oral condition reflects inherent nasalance differences across vowel qualities (Bell-Berti, 1993).

#### 4.2.2 Contrastive nasal $[\tilde{V}\tilde{V}]$ and nasal harmony

Figure 8 displays GAM curves fit to nasalance at each of the 33 timesteps across the  $[VGV]$  sequence for the oral  $[VGV]$  and contrastive nasal  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  conditions, for all fifteen speakers.<sup>11</sup> As expected, the oral  $[VGV]$  condition exhibits a relatively stable nasalance at about 20% across the entire  $[VGV]$  sequence. Tokens from the contrastive nasal  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  condition, on the other hand, show an increase in nasalance from the onset of the penultimate, pre-glide stem vowel until a plateau of nasalance is reached about a third of the way through the pre-glide vowel, and maintained

<sup>11</sup>Because nasalance measurements were taken at 11 equidistant timesteps for each segment, Figure 8 and other similar figures reporting nasality across  $[VGV]$  sequences involve some distortion in time. For instance, glides were typically much shorter than either of the vowels in any given token, and so the time steps during  $[G]$  in Figure 8 are not strictly comparable to the time steps for the adjacent vowels.

through the end of the word. This pattern is qualitatively consistent with a process of nasal harmony triggered by the final / $\tilde{V}\tilde{V}$ / vowel and targeting both the glide and the penultimate pre-glide vowel. The initial slope in nasalance across the first third of the penultimate pre-glide vowel is likely due to the transition out of an oral onset consonant. In sum, the GAM curves highlight a clear and relatively stable distinction in nasalance between the oral [VG $\tilde{V}$ ] and contrastive nasal [ $\tilde{V}\tilde{G}\tilde{V}$ =CV] conditions across the length of the [VG $\tilde{V}$ ] sequence.

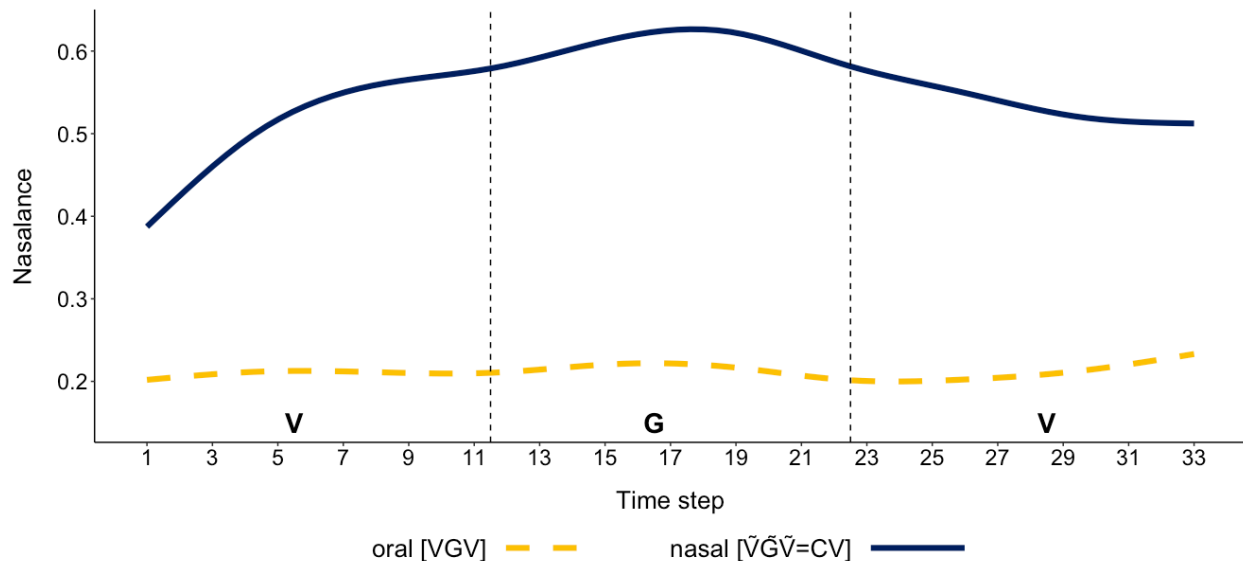


Figure 8: GAM curves for the oral [VG $\tilde{V}$ ] and contrastive nasal [ $\tilde{V}\tilde{G}\tilde{V}$ =CV] conditions in Experiment 2. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VG $\tilde{V}$ ] sequence for all 15 speakers in the experiment. Vertical dashed lines represent segment boundaries.

#### 4.2.3 Nasality of [ $\tilde{V}\tilde{V}\tilde{N}$ ] vowels

The crucial condition in this experiment is pre-N [VG $\tilde{V}\tilde{N}$ ]. The GAM curves in Figure 9 show that nasalance on the penultimate, pre-glide stem vowel does not diverge from the oral [VG $\tilde{V}$ ] condition with respect to nasalance until the latter portion of the pre-glide vowel, at which point a cline-like increase in nasalance begins and continues through the onset of the [ $\tilde{V}\tilde{V}\tilde{N}$ ] vowel. Strikingly, nasalance on the final vowel itself in the [ $\tilde{V}\tilde{V}\tilde{N}$ ] condition resembles the level of nasalance found on the final vowel in the contrastive nasal [ $\tilde{V}\tilde{G}\tilde{V}$ =CV] condition through most of its duration. A faceted visualization of these results is provided in Section 7.4 of the Appendix, demonstrating the stability of this pattern across the thirteen speakers.

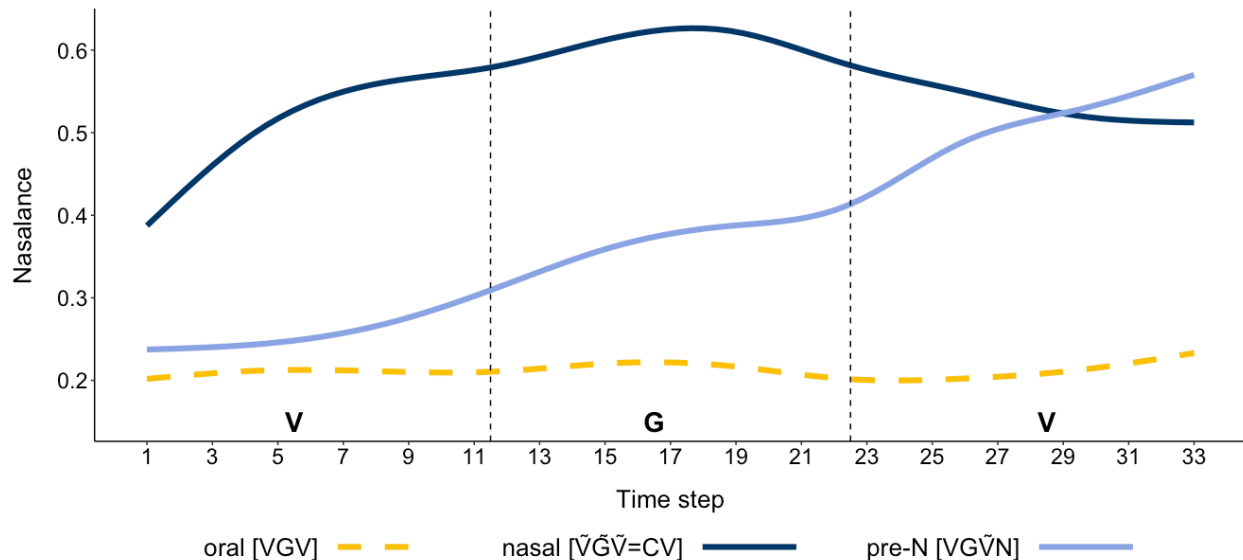


Figure 9: GAM curves for the oral [VG̃V], contrastive nasal [ṼG̃Ṽ=CV], and pre-N [VG̃VN] conditions in Experiment 2. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VG̃V] sequence for the 13 speakers in the experiment who categorically nasalized the word-final vowel in the pre-N [VG̃VN] condition. Dashed vertical lines represent segment boundaries.

To confirm that the pre-N [ṼVN] vowels in the pre-N [VG̃VN] condition are not different in nasalance to contrastive nasal vowels in the [ṼG̃Ṽ=CV] condition, we ran a linear mixed effects model (Table 4) comparing nasalance on the final stem vowel in the contrastive nasal [ṼG̃Ṽ=CV] and pre-N [VG̃VN] conditions. CONDITION (2 levels) was included as a dummy-coded main effect, and — due to the visual change in nasalance over time for both target vowels in Figure 9 — TIMESTEP (3 levels) and its interaction with CONDITION were also included as fixed effects. As before, TIMESTEP was effect-coded, and its three levels roughly correspond to the first third, middle third, and final third of the final vowel in the [VG̃V] sequence. In addition, including an effect-coded main effect of VOWELQUALITY (4 levels) resulted in a significantly better fit to the data ( $\chi^2(3) = 14.40, p = .002^{**}$ ), so it was retained in the model. By-word random intercepts were included, along with by-speaker random intercepts and random slopes for condition. All levels of the effect-coded main effects are included in the model output displayed in Table 4 for clarity.

With a closer inspection of the final three rows in Table 4, it is clear that the interaction between CONDITION and TIMESTEP is significant, with the nasalance of final stem vowels in pre-N [VG̃VN] diverging significantly from the final contrastive nasal [ṼG̃Ṽ=CV] stem vowel at each portion of the vowel. In the first third of the vowel, the pre-N [ṼVN] vowel was less nasalized, but in the final two thirds it was significantly more nasalized compared to that of the final contrastive nasal [ṼṼ/ vowel. Given these significant interaction effects and their nontrivial effect sizes, comparisons between the two vowel types must be analyzed at each time step level, rather than examining the main effect of vowel type as a whole.

| Predictor                          | $\beta$ | 95% CI         | $t$   | $p$        |
|------------------------------------|---------|----------------|-------|------------|
| Intercept (final V in [ṼG̃Ṽ=CV]) | .558    | [.494, .622]   | 17.08 | < .001 *** |
| final V in pre-N [VG̃VN]           | .005    | [-.053, .064]  | .17   | .86        |
| Beg                                | .023    | [.019, .026]   | 13.04 | < .001 *** |
| Mid                                | -.006   | [-.009, -.002] | -3.23 | .001 **    |
| Fin                                | -.017   | [-.021, -.013] | -8.68 | < .001 *** |
| ii                                 | .123    | [.062, .183]   | 3.96  | .004 **    |
| ee                                 | -.019   | [-.064, .025]  | -.86  | .41        |
| εε                                 | -.051   | [-.116, .014]  | -1.55 | .16        |
| αα                                 | -.052   | [-.086, -.019] | -3.04 | .02 *      |
| final V in pre-N [VG̃VN]:Beg       | -.078   | [-.081, -.072] | -31.3 | < .001 *** |
| final V in pre-N [VG̃VN]:Mid       | .017    | [.012, .022]   | 6.99  | < .001 *** |
| /final V in pre-N [VG̃VN]:Fin      | .060    | [.054, .065]   | 21.76 | < .001 *** |

Table 4: Results of the lmer model – lmer(nasalance~CONDITION\*TIMESTEP + VOWELQUALITY + (1 + CONDITION|speaker) + (1|word)) – estimating nasalance across the final vowel for 13 speakers who categorically nasalize pre-N [ṼVN] vowels. CONDITION was dummy coded, and effect-coded fixed effects include TIMESTEP and VOWELQUALITY.

In an effort to compare nasalance values between the two conditions more closely, we established a new Region of Practical Equivalence (*RoPE*) for contrastive nasal vowels in the nasal [ṼG̃Ṽ=CV] condition in the same way as described for Experiment 1, arriving at a value of  $\pm .051$ . For the beginning third of the vowel, the lower bound of the 95% CI in Table 4 extends well below  $-.051$ , suggesting that pre-N [ṼVN] vowels in the pre-N [VG̃VN] condition are significantly less nasalized than final nasal vowels in the nasal [ṼG̃Ṽ=CV] condition at this time juncture in the vowel. As we argue in the next section, this difference in nasalance is likely a consequence of the fact that nasal harmony applies in contrastive /VVG̃Ṽ/ → [ṼṼ.G̃ṼṼ], but not in pre-N /VVG̃VN/ → [VV.G̃ṼVN]. If the glide is fully nasalized in [ṼṼ.G̃ṼṼ] but not in [VV.G̃ṼVN], then observance of an oral-to-nasal transition between the beginning of the final vowel and the preceding glide in [VV.G̃ṼVN] is not unexpected.

Moreover, while the 95% CI for the middle third of pre-N [ṼVN] vowels in the pre-N [VG̃VN] condition in Table 4 falls within the *RoPE*, the 95% CI for the final third of the vowel falls entirely *above* the *RoPE*. This means that pre-N [ṼVN] vowels are significantly more nasalized than contrastive nasal vowels in this region. This nasality difference is consistent with the influence of the following context: pre-N [ṼVN] vowels in the pre-N [VG̃VN] condition precede a nasal consonant, which maximizes nasalance, whereas the nasal vowels in the stem-final syllable of the nasal [ṼG̃Ṽ=CV] condition precede an oral stop, which typically exhibits minimal nasalance.

Taking the effects of context into account, it seems reasonable to conclude that contrastive nasal vowels in the stem-final syllable of the nasal [ṼG̃Ṽ=CV] condition and pre-N [ṼVN] vowels in the pre-N [VG̃VN] condition are both targeted as [+NAS], not only in monosyllabic tokens (experiments 1) but in longer words as well. Apparent differences between them arise from different patterns of local, nasal coarticulation on the preceding glide and following consonant.

#### 4.2.4 Nasal Harmony

Having confirmed that non-alternating pre-N [VG $\tilde{V}$ N] vowels and contrastive nasal [V $\tilde{G}\tilde{V}$ =CV] are both targeted as [+NAS] in the tokens used in Experiment 2, we can now quantitatively examine whether the two vowel types differ in how they trigger nasal harmony.

From a cursory examination of the GAM curves in Figure 9 above, it seems clear that the two vowel types — non-alternating, pre-N [VG $\tilde{V}$ N] and underlying contrastive nasal [V $\tilde{G}\tilde{V}$ =CV] — interact in a qualitatively distinct manner with the nasal harmony process. To corroborate these facts quantitatively, we ran two separate models to examine nasalance on the glides and the penultimate vowels in the [VG $\tilde{V}$ ] sequence, respectively.

##### 4.2.4.1 Nasal Harmony is Not Triggered by [V $\tilde{V}$ N]: Glides in pre-N [VG $\tilde{V}$ N]

The results of the model comparing the glides in the contrastive nasal [V $\tilde{G}\tilde{V}$ =CV] and pre-N [VG $\tilde{V}$ N] conditions are given in Table 5. The data in this model is limited to the thirteen speakers who categorically nasalize pre-N [V $\tilde{V}$ N] vowels in the pre-N [VG $\tilde{V}$ N] condition in Experiment 2; see section 7.5 of the Appendix for discussion of the remaining two speakers.

The model’s intercept is the stem-final /V $\tilde{V}$ / vowel in the nasal [V $\tilde{G}\tilde{V}$ =CV] condition. Contrastive nasal /V $\tilde{V}$ / vowels were included in the model in order to compare the glides in the two conditions to a segment that is clearly categorically [+NAS]. Doing so provides a clearer picture as to whether [V $\tilde{V}$ N] vowels are triggering nasal harmony in the pre-N [VG $\tilde{V}$ N] condition.

The glide in the contrastive nasal [V $\tilde{G}\tilde{V}$ =CV] condition is significantly more nasalized than the contrastive nasal /V $\tilde{V}$ / vowel that follows it (as is evident in Figure 9). The increased nasalance on the glide in contrastive [V $\tilde{G}\tilde{V}$ =CV] relative to nasal vowels is likely due to the fact that glides have narrower constrictions in the oral cavity than vowels. All else being equal, narrowed oral constrictions will force a greater proportion of overall airflow through the nasal cavity (e.g. Bell-Berti 1993, Delvaux et al. 2008, p.595). In any case, these results provide clear support for the claim that the glide in /VVG $\tilde{V}$ =CV/ → [V $\tilde{V}$ . $\tilde{G}\tilde{V}$ =CV] strings is targeted for nasal harmony, triggered by the stem-final /V $\tilde{V}$ /.

For glides in the pre-N [VG $\tilde{V}$ N] condition, on the other hand, mean nasalance falls significantly below the mean nasalance of the contrastive nasal /V $\tilde{V}$ / vowels in the [V $\tilde{G}\tilde{V}$ =CV] condition (by 16.7%). The 95% confidence interval for the difference falls entirely outside (and below) the proposed *RoPE* ( $\pm .051$ ), confirming they are less nasalized than stem-final [V $\tilde{G}\tilde{V}$ =CV] vowels. We therefore conclude that, unlike glides preceding contrastive nasal /V $\tilde{V}$ / vowels, glides preceding a non-alternating [V $\tilde{V}$ N] vowel are not targets of nasal harmony.

| Predictor                                           | $\beta$ | 95% CI         | $t$   | $p$        |
|-----------------------------------------------------|---------|----------------|-------|------------|
| Intercept (Final V in [V $\tilde{G}\tilde{V}$ =CV]) | .538    | [.475, .600]   | 16.83 | < .001 *** |
| glide ([V $\tilde{G}\tilde{V}$ =CV] condition)      | .068    | [.048, .087]   | 6.83  | < .001 *** |
| glide (pre-N [VG $\tilde{V}$ N] condition)          | -.167   | [-.232, -.100] | -4.92 | < .001 *** |

Table 5: Results of the lmer model estimating mean nasalance of the glide in the [VG $\tilde{V}$ ] sequence for 13 speakers. CONDITION was included as a dummy-coded fixed effect. The final /V $\tilde{V}$ / in the [V $\tilde{G}\tilde{V}$ =CV] condition serves as the intercept in the model, and the estimates for the other predictors describe the predicted deviation from the intercept: lmer(nasalance~CONDITION + (1 + CONDITION|speaker) + (1|word)).

#### 4.2.4.2 Nasal Harmony is Not Triggered by [ĩĩN]: Penult stem vowels in pre-N [VGĩN]

We now turn to a model comparing nasalance of the penultimate, pre-glide stem vowels in the pre-N [VGĩN], oral [VGv], and contrastive nasal [ĩĩĩ=CV] conditions. The results of this model are summarized in Table 6. Here, penultimate stem vowels in oral [VGv] serve as the intercept: the goal is to determine whether penultimate stem vowels in the pre-N [VGĩN] condition significantly differ from those in the oral [VGv] condition.

The model coefficients indicate that the penultimate pre-glide stem vowel in the contrastive nasal [ĩĩĩ=CV] condition exhibits about 34% more nasalance than in the oral [VGv=CV] condition baseline. In the pre-N [VGĩN] condition, the penultimate pre-glide stem vowel does not significantly differ from the oral baseline vowel. However, we computed a *RoPE* of  $\pm .033$  for penultimate oral vowels, and the upper bound of the 95% CI for the oral vs. [ĩĩĩN] difference extends outside this region. Thus, while a distinction in nasalization between penultimate pre-glide stem vowels in the pre-N [VGĩN] and oral [VGv] conditions cannot be ruled out, the estimated difference in nasalization from the oral [VGv] condition is about 27% smaller than the difference between the oral baseline and the contrastive nasal [ĩĩĩ=CV] condition.

| Predictor                          | $\beta$ | 95% CI       | <i>t</i> | <i>p</i>   |
|------------------------------------|---------|--------------|----------|------------|
| Intercept (penult V in oral [VGv]) | .194    | [.132, .255] | 6.20     | < .001 *** |
| penult V in pre-N [VGĩN]           | .069    | [.005, .133] | 2.12     | .05        |
| penult V in ([ĩĩĩ=CV])             | .338    | [.274, .402] | 10.36    | < .001 *** |

Table 6: Results of the lmer model estimating mean nasalance of the penultimate, pre-glide stem vowel in the [VGv] sequence for 13 speakers who categorically nasalize pre-N [ĩĩĩN] vowels in the pre-N [VGĩN] condition. CONDITION (penultimate stem vowel (oral [VGv], pre-N [VGĩN], nasal [ĩĩĩ=CV])) was included as a dummy-coded fixed effect. The intercept is the penultimate stem vowel in the oral [VGv] condition: lmer(nasalance~CONDITION + (1 + CONDITION|speaker) + (1|word)).

### 4.2.5 Summary of results for Experiment 2

To summarize, non-alternating, pre-N [ĩĩĩN] vowels and contrastive nasal /ĩĩĩ/ vowels are both targeted by speakers as [+NAS] vowels when uttered in the final position of a [VGv] sequence, replicating results from Experiment 1. Despite the similar surface nasality on the stem-final vowels in pre-N [VGĩN] and contrastive nasal [ĩĩĩ=CV] conditions, pre-N [ĩĩĩN] and contrastive nasal /ĩĩĩ/ triggered distinct patterns of nasalization across the preceding [VG] sequence. The segments preceding the contrastive nasal /ĩĩĩ/ vowel were significantly nasalized across the entire span, to a similar degree as the contrastive nasal /ĩĩĩ/ vowel itself. This confirms previous impressionistic descriptions that contrastive nasal /ĩĩĩ/ vowels in Panjabi trigger leftward nasal harmony across [VG] sequences, affecting both preceding vowels and glides (albeit optionally).

Conversely, [VG] sequences preceding pre-N [ĩĩĩN] exhibited a different pattern of nasality. The immediately preceding glide in the pre-N [VGĩN] condition was significantly less nasalized than in the contrastive nasal [ĩĩĩ=CV] condition; in contrast, glides preceding the final contrastive nasal /ĩĩĩ/ in the [ĩĩĩ=CV] condition exhibited similar nasalance to contrastive nasal /ĩĩĩ/. This is consistent with our claim that glides are nasalized by harmony when they precede contrastive nasal /ĩĩĩ/, but not when they precede pre-N [ĩĩĩN].

For the pre-N [VG̃VN] condition, nasalance is low on the glide, and apparently even lower on the penultimate stem vowel (Figure 9). In other words, nasality steadily declines in strength for segments which are further away from the [ṼVN] vowel, which we analyze as the only phonologically nasalized segment in the [VVG̃VN] string (setting aside the nasal consonant).

Nasalance on the penultimate pre-glide stem vowel in pre-N [VG̃VN] was not found to significantly differ from nasalance on the penultimate pre-glide stem vowel in the oral [VGV] condition. Thus, the pre-N vowel in [ṼVN] is itself targeted as [+NAS], but does not trigger nasal harmony across the preceding glide and penultimate, pre-glide stem vowel in [VVG̃VN]. Any vestigial nasality on the glide and pre-glide vowel appears to reflect lower-level, local coarticulation for nasality rather than nasal harmony as such.

In the following two sections, we evaluate alternative analyses of the nasality patterns observed in Experiment 2. These analyses attribute the distinct nasality patterns in the contrastive nasal [ṼG̃V=CV] and pre-N [VG̃VN] conditions, not as the differential application of nasal harmony, but instead to either stress differences between the two conditions (section 4.3) or a fixed nasality window spanning different portions of the [VGV] sequence in each condition (section 4.4). Ultimately, we show that neither account is well motivated.

### 4.3 Nasalization Reflects Harmony, not Coarticulation

A potential confound in our interpretation of nasalance values in the contrastive nasal [ṼG̃V=CV] vs. pre-N [VG̃VN] conditions comes from stress placement. Stress has been described as weight sensitive in Panjabi, though in somewhat inconsistent terms (Bashir and Connors 2019; Bhatia 1993; Dhillon 2007; Hussain et al. 2019; Shackle 2003). Both stem syllables in the contrastive [ṼG̃V=CV] condition are bimoraic, whereas, for pre-N [VG̃VN], the penultimate syllable is bimoraic, and the final syllable at least plausibly trimoraic. These differences in syllable weight could affect stress placement across conditions. If so, based on some prior descriptions of weight-sensitive stress in Panjabi (e.g. Bashir and Connors 2019), we might expect penultimate stress on [ṼṼ.G̃ṼṼ], and final stress on [VṼ.G̃ṼVN].

Stress has also been found to correlate with increased nasality in some contexts and languages (e.g. Avelino et al. 2020; Krakow 1989; Zellou 2022 and references therein). This at least raises the possibility that the increased nasalance on the glide and penultimate pre-glide vowel in the contrastive nasal [ṼG̃V=CV] condition may not represent nasal harmony, but could instead result from long-distance coarticulation for nasality between the stressed penultimate syllable and the final contrastive nasal vowel.<sup>12</sup>

Since increased vowel duration is found to be a correlate of stress in many of the world's languages (van Heuven and Turk, 2021), we can try to assess this claim by comparing the mean duration of the penultimate and final vowels across the two conditions of most interest, contrastive nasal [ṼG̃V=CV] vs. pre-N [VG̃VN]. The penultimate and final stem vowels in the [ṼG̃V=CV] condition were 106 ms and 103 ms in mean duration, respectively, compared to a mean duration of 65 ms for the penultimate stem vowel and 151 ms for the final stem vowel in the pre-N [VG̃VN] condition. These measurements are at least consistent with the claim that contrastive nasal [ṼG̃V=CV]

<sup>12</sup>To our knowledge, reported effects of stress on nasal coarticulation involve local interactions between [NV] and [VN] sequences, rather than the kind of longer-distance effects we are entertaining here. We nonetheless consider this scenario in the interest of ruling it out as a possible counter-explanation, particularly since nasal coarticulation is known to occur over a wide timespan in some languages (e.g. Pouplier et al. 2024).

and pre-N [VG̃VN] differ with respect to stress placement, stress being penultimate in the former case, and final in the latter. However, Bhatia (1993, p.343) offers an impressionistic description that vowel duration is unaffected by stress placement, which complicates a straightforward interpretation of these results.

Regardless, even if stress is responsible for vowel length differences between the two conditions, this does not entail that we should see the drastic nasality differences reported here. In at least some languages where stress conditions greater nasal coarticulation, there is a positive correlation between the duration of the stressed vowel and the degree of nasalance on that vowel (e.g. discussion in Zellou 2022, p.21, 35). However, no such correlation, positive or negative, is present in our data. Considering all forms in the contrastive nasal [VG̃VN=CV] and [VG̃VN=NV] conditions (including those that do not exhibit categorical nasal harmony), a Pearson’s correlation analysis ( $r(723) = -.05$ ,  $p = .22$ ) between penultimate pre-glide stem vowel duration and mean nasalance on the penultimate pre-glide stem vowel did not detect a significant effect (Figure 10), and the magnitude of the correlation coefficient is quite small.

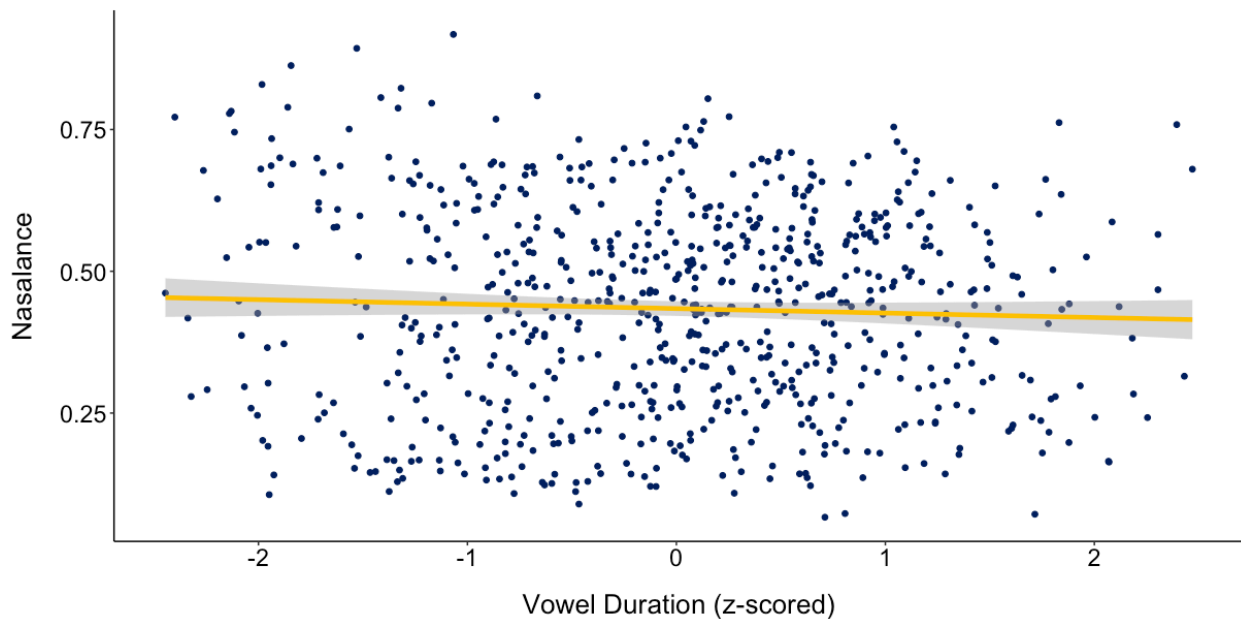


Figure 10: Scatterplot showing the estimated  $-.05$  Pearson Correlation value between penultimate pre-glide stem vowel duration (using by-speaker z-scored values) and mean nasalance in the contrastive nasal [VG̃VN=CV] and [VG̃VN=NV] conditions.

If the nasal harmony pattern observed in the contrastive nasal [VG̃VN=CV] condition reflected long-distance coarticulation conditioned by stress, we would expect at least *some* association between nasalance and vowel duration, be it positive or negative. The lack of such a correlation argues against treating nasal harmony as a phonetic process of nasal coarticulation, rather than a phonological process of nasal spreading. (We return to this point in section 4.4.)

In sum, the uncertainty about the phonetic correlates of stress in the language and the finding that nasalance on the penultimate pre-glide vowel in contrastive nasal [VG̃VN=CV] and [VG̃VN=NV] conditions is insensitive to duration all argue against re-analyzing nasal harmony as a stress-sensitive process of long-distance nasal coarticulation. While further work on the phonetics of

stress in Panjabi would of course be welcome, at present we see no reason to treat the high levels of nasality on the penultimate stem vowel of the contrastive nasal [ĩĩĩĩ=CV] condition as anything other than the result of a categorical process of phonological nasal harmony (see also section 4.4).

#### 4.4 Harmony does not Reflect a Fixed Nasalization Window

We have argued that nasality spreads leftward to the penultimate pre-glide stem vowel in the contrastive nasal [ĩĩĩĩ=CV] condition in Panjabi, but not in the pre-N [VGĩN] condition. We have further argued that spreading is best construed as a phonological harmony process which propagates the abstract feature [+NAS] leftward from contrastively nasal vowels in the [ĩĩĩĩ=CV] condition, but not from predictable, contextually nasal vowels in the pre-N [VGĩN] condition.

An alternative analysis of this data might be possible in which nasalization in the contrastive nasal [ĩĩĩĩ=CV] condition owes to a coarticulatory window in which the velum is lowered for a more or less fixed period of time. Assume that in both [ĩĩĩĩĩĩĩĩ] and [VV.GĩĩN] there is a *fixed period* of nasality anchored at the right edge of the word (see e.g. Beddor 2007). If so, we might expect nasality to begin later in [. . . VV.GĩĩN] than in [. . . ĩĩĩĩĩĩĩĩ], because the additional, word-final nasal segment in [. . . VV.GĩĩN] would cause the overall ‘window’ of nasality to shift rightward. This difference in the timing of phonetic nasality could give the impression of a difference in the application of harmony, without implicating a harmony process as such.

There are at least three arguments against this analysis. The first comes from the optionality of nasal harmony in Panjabi (section 4.2). Leftward nasal spreading in contrastive nasal [ĩĩĩĩ=CV] often yields nasalized [ĩĩĩĩĩĩĩĩ], but outcomes in which harmony fails to apply [VVGĩĩĩ] are also frequent across all items and speakers. If there is a fixed period of velar lowering in all words that end in a nasal segment, then the non-application of nasal harmony in [ĩĩĩĩ=CV] is quite puzzling. On the other hand, if nasal harmony is an abstract phonological process, then categorical variation between nasalized [ĩĩĩĩĩĩĩĩ] and non-nasalized [VVGĩĩĩ] can be straightforwardly analyzed as optional rule application (see also Plug et al. 2019).

Second, in section 4.3 we observed that there is no correlation between the duration of the penultimate pre-glide vowel in the contrastive nasal [ĩĩĩĩ=CV] and [ĩĩĩĩ=NV] conditions and the degree of nasalance on that vowel. This result is again surprising if harmony owes to a coarticulatory window of approximately fixed duration: in that scenario, we should see a decrease in nasalance as the pre-glide vowel grows longer, and more distant from the phonetic source of nasality at the right edge of the word in [ĩĩĩĩĩĩĩĩ] (e.g. Solé 1992, 1995).

Finally, a third argument against this approach comes from the analysis of nasalization in the contrastive nasal [ĩĩĩĩ=NV] condition. If contrastive nasal /ĩĩĩ/ vowels are responsible for triggering nasal harmony — understood as a phonological process — the presence of a following /=NV/ postposition should not affect the application of harmony in any way in /VVGĩĩĩ/. Conversely, if the consistent nasalance in the [ĩĩĩĩ=CV] condition is due to the anchoring of a fixed window of nasalization to the right edge of the rightmost nasal segment, we would expect this window to shift to the right to align with the initial nasal consonant of the postposition. In this scenario, nasalization in [ĩĩĩĩ=NV] should mirror the nasalance pattern of the pre-N [VGĩN] condition: there should be no evidence of harmony.

Each item in the [ĩĩĩĩ=CV] condition was also produced in a corresponding [ĩĩĩĩ=NV] context in our study. This allows for a direct comparison of nasality across the two conditions. The GAM

curve for all fifteen speakers for the  $[\tilde{V}\tilde{G}\tilde{V}=NV]$  condition is provided in Figure 11, alongside the baseline oral  $[VG\tilde{V}]$  and contrastive nasal  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  conditions for comparison.

As is evident from Figure 11, the  $[\tilde{V}\tilde{G}\tilde{V}=NV]$  condition shows a high degree of nasalance across the entire  $[VG\tilde{V}]$  sequence, closely resembling the nasalance contour for the  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  condition (oral postposition). The slight difference in nasality at the very end of  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  vs.  $[\tilde{V}\tilde{G}\tilde{V}=NV]$  undoubtedly reflects local coarticulation with the following /C/ in  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  vs. /N/ in  $[\tilde{V}\tilde{G}\tilde{V}=NV]$ .

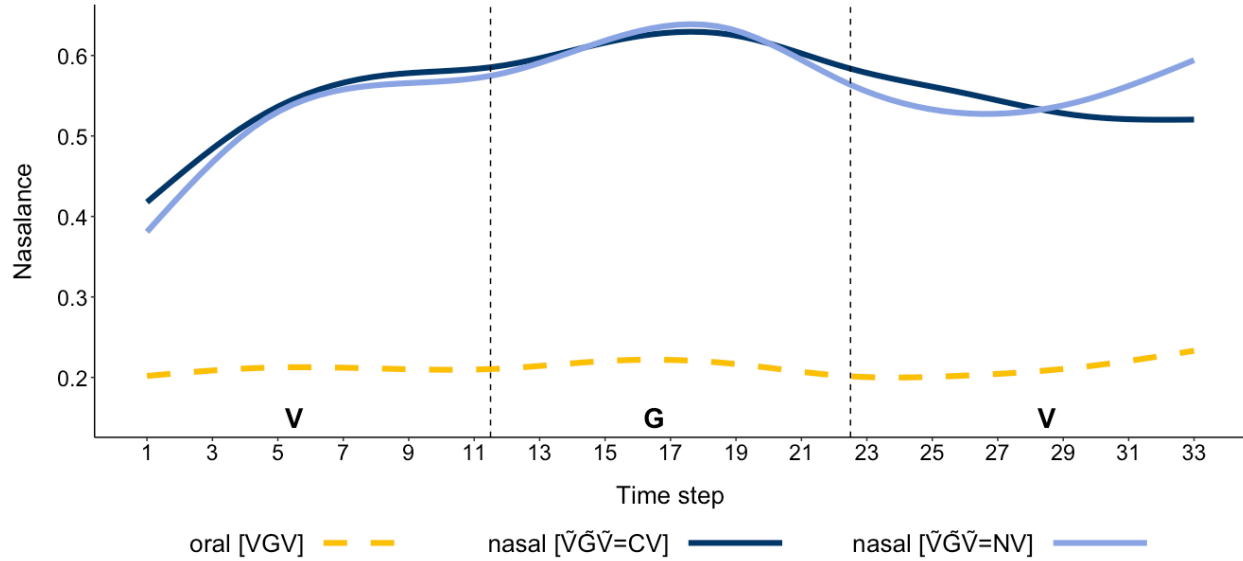


Figure 11: GAM curves comparing the contrastive  $[\tilde{V}\tilde{G}\tilde{V}=NV]$  condition to the oral  $[VG\tilde{V}]$  and contrastive nasal  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  conditions. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the  $[VG\tilde{V}]$  sequence for each condition for all fifteen speakers.

A lmer model estimating the difference between the penultimate pre-glide stem vowels in the  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  and  $[\tilde{V}\tilde{G}\tilde{V}=NV]$  conditions in Table 7 shows that the mean nasalance of the penultimate pre-glide stem vowel in the  $[\tilde{V}\tilde{G}\tilde{V}=NV]$  condition is not significantly different from the mean nasalance of the penultimate pre-glide stem vowel in  $[\tilde{V}\tilde{G}\tilde{V}=CV]$ .

| Predictor                                                   | $\beta$ | 95% CI        | $t$   | $p$        |
|-------------------------------------------------------------|---------|---------------|-------|------------|
| Intercept (Penult V in $[\tilde{V}\tilde{G}\tilde{V}=CV]$ ) | .507    | [.424, .589]  | 12.03 | < .001 *** |
| Penult V in $[\tilde{V}\tilde{G}\tilde{V}=NV]$              | -.012   | [-.100, .077] | -.26  | .80        |

Table 7: Results of the lmer model estimating mean nasalance of the penultimate vowel in the  $[VG\tilde{V}]$  sequence for 15 speakers. CONDITION with two levels (penultimate pre-glide stem vowel ( $[\tilde{V}\tilde{G}\tilde{V}=CV]$ ) and penultimate pre-glide stem vowel ( $[\tilde{V}\tilde{G}\tilde{V}=NV]$ )) was included as a dummy-coded fixed effect. The intercept is the penultimate pre-glide stem vowel in the  $[\tilde{V}\tilde{G}\tilde{V}=CV]$  condition: lmer(nasalance~CONDITION + (1 + CONDITION|speaker) + (1|word)).

We conclude that the results of Experiment 2 cannot be analyzed by assuming that a nasalization window of approximately fixed length is anchored at the right edge of the rightmost nasal segment. The results are most straightforwardly consistent with a phonologically-controlled, optional harmony process which spreads nasality leftward from contrastive nasal vowels  $/\tilde{V}\tilde{V}/$ , but not from derived, predictable pre-N  $[\tilde{V}\tilde{V}N]$  vowels.

## 4.5 Summary of Experiment 2

This experiment sought to uncover how [ĩĩN] vowels interact with nasal harmony in Panjabi. While the results of this experiment and Experiment 1 confirm that pre-N [ĩĩN] vowels show statistically equivalent nasality to underlying /ĩĩ/ vowels, section 4.2.2 showed they do not trigger nasal harmony like contrastive nasal /ĩĩ/ vowels. In the following section we argue that this phonological difference between contrastive nasal /ĩĩ/ and predictably nasal [ĩĩN] vowels is best analyzed by assuming that surface [ĩĩN] reflects an underlying oral vowel, /VVN/ — in other words, a covert UR.

## 5 Discussion

### 5.1 Analyzing [ĩĩN] vowels in Panjabi with abstract URs

The above experiments established several facts about non-alternating [ĩĩN] vowels in Panjabi. First, these vowels are phonologically nasal on the surface. Their realization mirrors the categorical nasality of contrastive nasal /ĩĩ/ vowels in both experiments, and changes in speech rate do not impact the degree of nasalization on pre-N [ĩĩN] vowels. Nonetheless, derived nasal vowels in the pre-N [VGĩĩN] condition differ from contrastive nasal vowels in [ĩĩĩĩ=CV] and [ĩĩĩĩ=NV] in failing to trigger leftward nasal harmony: /VVGĩĩĩĩ/ → [ĩĩĩĩ.ĩĩĩĩ], but /VVGVVN/ → [VV.GĩĩĩĩN], \*[ĩĩĩĩ.ĩĩĩĩN] (Experiment 2).

The interaction between nasal harmony and [ĩĩN] vowels can be handled straightforwardly within any framework that (i) permits covert URs, and (ii) has mechanisms for generating counterfeeding opacity. Here, we provide an analysis using ordered rewrite rules (e.g. Chomsky and Halle 1968), but various other approaches are also viable. We gloss over the optionality of nasal harmony, but this simplification has no consequences for our overall analysis.

The derivation in (5) produces an opaque interaction between nasal harmony and the contextual nasalization of pre-N vowels in /VVN/ → [ĩĩN] (which we dub ‘assimilation’ in (5)). In (5a), the word-final nasal vowel /ẽẽ/ is present underlyingly. Harmony is the first rule to apply in the derivation, so it can only be sensitive to underlying structure. As such, harmony is triggered by the final /ẽẽ/ in /tʃaavẽẽ/ → [tʃããũẽẽ] ‘pumicstone’, as desired.

(5) Counterfeeding between nasal harmony and nasal assimilation in Panjabi

|               |                                                     |              |             |
|---------------|-----------------------------------------------------|--------------|-------------|
|               |                                                     | a. /tʃaavẽẽ/ | b. /aavaam/ |
| Harmony:      | $[-CONS] \rightarrow [+NAS]/\_X_0[-CONS]V_{[+NAS]}$ | tʃããũẽẽ      | -           |
| Assimilation: | $V \rightarrow [+NAS]/\_C_{[+NAS]}$                 | -            | aavããm      |
|               |                                                     | [tʃããũẽẽ]    | [aavããm]    |

In (5b), the [ĩĩN] vowel is underlyingly oral in /aavaam/ ‘general public’. Since harmony is the first rule to apply, it cannot ‘know’ that the final vowel of /aavaam/ will eventually be nasalized by the assimilation rule in (5) — harmony is only sensitive to underlying nasality, not derived, predictable nasality. As such, harmony fails to apply to /aavaam/. The underlying form /aavaam/ subsequently undergoes assimilation, producing the surface form [aavããm]. This is a textbook case of counterfeeding opacity: assimilation applies ‘too late’ in the derivation to feed nasal harmony (e.g. Baković 2011; Baković and Blumenfeld 2024; Kiparsky 1973; Wiese 2000).

To reiterate a crucial aspect of our analysis, underlying representations like /aɑvaɑm/ are *covert* in Panjabi, because pre-N vowels in non-alternating morphemes never actually surface as oral. The use of covert URs is a centerpiece of the analysis in (5): it is the key to distinguishing between derived (predictable) and contrastive (unpredictable) nasality for the purposes of determining when nasal harmony applies.

Although we analyze all pre-N vowels before a tautosyllabic nasal coda as underlyingly oral and systematically neutralized to nasal, this differs from the kind of *absolute neutralization* rejected by Kiparsky (1982, p. 127–135). As Kiparsky defines it, absolute neutralization eliminates a phonological distinction in *every* environment, as with the abstract glide-like phoneme, /ɛ/, proposed word-finally by Chomsky and Halle (1968) for English words such as *tolerance*, which never surfaces. By contrast, Panjabi oral vowels surface freely elsewhere (e.g., [bɑ:t] ‘story’) and are neutralized only, but without exception, before nasal codas.

Our analysis also differs from other proposals involving covert URs, such as the account of Vago (1973) for exceptional Hungarian vowel harmony. In that proposal, covert URs preserve hidden lexical contrasts that trigger harmony but are distributed idiosyncratically and must be learned word by word. In Panjabi, by contrast, covert URs are assigned systematically: every vowel before a tautosyllabic nasal coda is underlyingly oral. Rather than invoking covert URs to preserve hidden lexical contrasts, the covert URs proposed here capture a productive and exceptionless neutralization process in which underlying oral vowels become nasal before nasal codas while remaining phonologically distinct from contrastive nasal vowels in their interaction with nasal harmony. This systematic behavior pushes against an analysis in which the pattern is merely a static phonotactic generalization lexicalized in a small set of exceptional forms.

To demonstrate that the pre-N nasal assimilation process in Panjabi is not a static phonotactic generalization fossilized in the words examined in this study, we can compare the pre-N forms from Experiment 2 — all of which lack a morpheme boundary between the pre-N vowel and following nasal consonant — with forms containing an underlyingly oral vowel that appear before a nasal consonant suffix. Although these forms were not analyzed as a primary condition in Experiment 2, all participants produced the words /veejɑɑ-ŋ/ ‘to marry-NOML’ and /geejɑɑ-ŋ/ ‘to know-NOML’ under the same elicitation procedure. In these forms, the vowel in the stem is oral in the absence of the nasal consonant suffix, but surfaces as nasal when the suffix is present. This is confirmed by the GAM curves in Figure 12, in which the underlyingly oral vowels followed by a nasal consonant suffix exhibit strikingly similar patterns to the tautomorphemic pre-N vowels from Experiment 2: they are systematically nasalized across the pre-N vowel itself, but they do not trigger nasal harmony across the preceding glide and vowel. This systematic nasalization of underlying oral vowels in combination with the lack of nasal spreading provides additional evidence that non-alternating pre-N vowels are underlyingly oral, and that their consistent surface nasalization reflects an active phonotactic alternation in Panjabi.

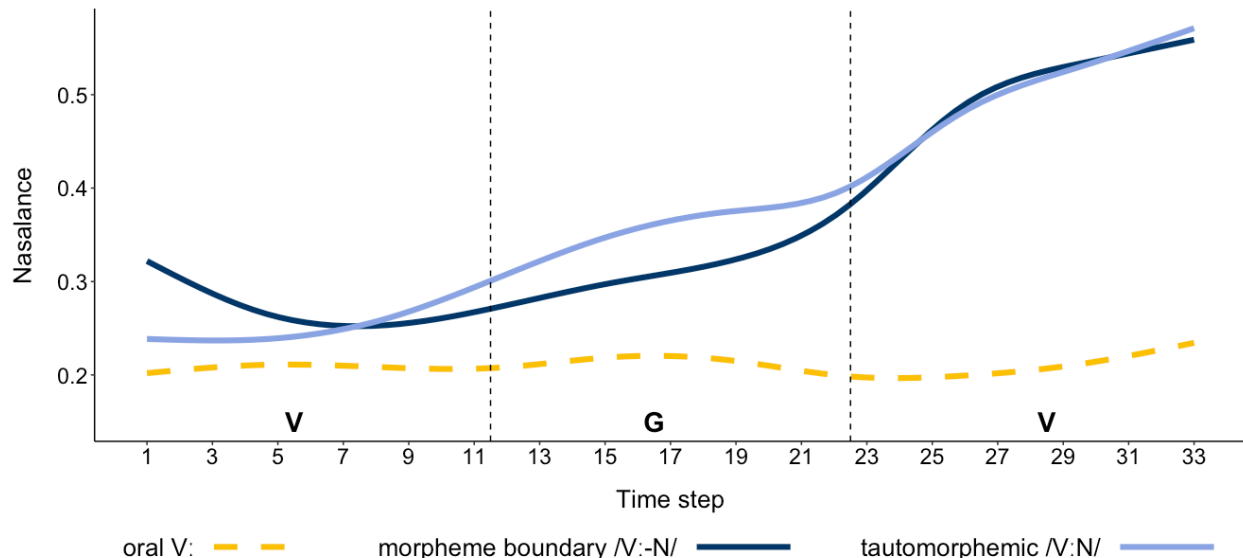


Figure 12: GAM curves comparing the tautomorphemic / $\tilde{V}\tilde{V}N$ / condition from Experiment 2 to forms with an underlying oral vowel followed by a nasal consonant suffix: morphemic boundary / $\tilde{V}\tilde{V}-N$ / ( $n = 104$ ). Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VGV] sequence for each condition for the thirteen speakers from Experiment 2 that categorically nasalize pre- $N$  vowels.

## 5.2 Panjabi nasal opacity: a challenge for surface-oriented frameworks

As demonstrated in the previous section, frameworks that permit covert URs offer a straightforward explanation for the nasal opacity patterns observed in Pakistani Panjabi. By contrast, theories that either reject URs altogether or tightly tether them to surface realizations struggle to account for these patterns. Such theories include eliminativist exemplar models (e.g. Bybee 2001; Johnson 1997, 2006; Pierrehumbert 2001) and surface-oriented generative approaches, in which symbolic URs are permitted but must correspond transparently to one of their surface forms (e.g. Albright 2002; Allen and Becker 2015; Burzio 1996; Cole and Hualde 2011; Hayes 1999; Scobbie et al. 1996; Wang and Hayes 2025). Although these approaches differ in the representational format they assume, they are unified by the claim that all linguistic generalizations must be recoverable from surface distributions—that is, they reject covert representations.

In the subsections that follow, we consider how each type of surface-oriented model might attempt to explain the Panjabi data and show that any theory lacking covert representations faces serious difficulty in capturing the opacity effects documented here.

### 5.2.1 Opacity in exemplar models

A primary concern of generative phonology has been the modeling of productive, general alternations in phonological systems. Consider the famous ‘Bach test’ of Halle (1978a): asked to pluralize the proper name *Bach* [bax], English speakers will uniformly provide [bax-s], as opposed to any of the other plural forms conceivably suggested by the vocabulary of English (\*[bax-z], \*[bax-iz], \*[bax-z], \*[bax-ən], etc.). This is a productive pattern of generalization inasmuch as (i) speakers

may have never heard, or themselves produced, the plural of *Bach* before, and (ii) the velar fricative [x] does not normally occur in English, so speakers have little or no direct evidence about how to pluralize forms ending in [x]. Traditionally, productive phonological generalization of this type has been modeled with abstract, feature based rules or other formal mechanisms (e.g. the voicing assimilation rule [-SON] → [αVOI]/[-SON, αVOI]\_\_# ; Halle 1978a).

Usage-based models like exemplar theory have not been equally concerned with modeling productive phonological generalizations and alternations of this type, though work in this vein does exist (see e.g. Goldrick and Cole 2023; Kaplan 2015; Kirchner 2011; Kirchner et al. 2010; Pierrehumbert 2006, 2016).<sup>13</sup> This is not to suggest that exemplar models lack mechanisms for productive generalization (as Pierrehumbert (2016) emphasizes). We are simply noting that the issue has received less attention in the exemplar theory literature than in generative phonology. Relatedly, the precise mechanisms that determine productive generalization in exemplar theoretic models remain a somewhat open question (e.g. how, exactly, ‘similarity’ is calculated between novel and stored forms for the purposes of pattern extension; how statistical regularities are actually computed for the purposes of learning phonotactics, etc. see, e.g. Albright and Hayes 2003; Becker et al. 2017, 2011, 2012; Daland et al. 2011; Du and Durvasula 2025; Gorman 2013; Gouskova and Becker 2013).

Examining vowel harmony systems under an exemplar-theoretic model, Cole (2009, p.155) argues that harmony processes may emerge due to a listener’s misperception of coarticulatory information as a perceptually informative feature of the segments targeted for harmony. In the case of nasal harmony in Panjabi, then, regular patterns of long-distance nasal coarticulation in [ŨǦŨ] sequences with a final contrastive nasal vowel could strengthen over time until a general pattern of harmony that resembles a formal grammatical processes emerges.<sup>14</sup> With that said, this model does not resolve the question of why pre-N [ŨŨN] vowels do not also trigger harmony. Moreover, such an analysis also gives rise to the overfitting issues discussed below.

Perhaps more to the point, we are not aware of any attempt within the exemplar theory literature to model regular, opaque interactions like the counterfeeding interaction between nasal assimilation and nasal harmony in Panjabi discussed in (5) (see also Ettlinger 2008, 2009; Kawahara 2001). For that reason, our assessment of exemplar theory and related models in this section is based on our own understanding of the framework, rather than any specific, previous proposals. Our focus is on ‘eliminativist’ exemplar theories — that is, theories which dispense with discrete, symbolic abstraction of the speech stream (Goldinger, 1998; Goldrick and Cole, 2023).

Several mechanisms have been proposed for producing some form of abstraction in exemplar theory. The first mechanism is at the very core of the theory: the storage of many, phonetically-detailed memory traces for individual lexical items (section 1). If production and perception are *mediated by some form of averaging* over these traces, the result is abstraction: any single production target, or perceptual classification, will reflect the aggregate structure of the exemplar cloud, rather than any single, specific, stored concrete exemplar (e.g. Goldinger 1998; Pierrehumbert 2001, 2002, 2003; Wedel 2004, 2006). This is a species of abstraction.

As we have argued above, surface, phonetic nasality is functionally equivalent in contrastive

<sup>13</sup>An infamous exception is the ‘English past-tense debate’; see e.g. Pinker (2002); Seidenberg and Plaut (2014). We note that this is a debate about morphological patterning (with phonological conditioning, Albright and Hayes 2003), where here we are concerned with purely phonological patterns.

<sup>14</sup>It is unclear how such reasoning could explain the categorical optionality of nasal harmony described in section 4.2.1.

nasal / $\tilde{V}\tilde{V}$ / and pre-N [ $\tilde{V}\tilde{V}$ N] in Panjabi. Consequently, no form of averaging over stored exemplars will produce an abstract difference between contrastive nasal / $\tilde{V}\tilde{V}$ / and pre-N [ $\tilde{V}\tilde{V}$ N] as such. We conclude that this first mechanism for abstraction in exemplar theory — averaging over stored exemplar clouds — doesn't provide any insight into why contrastive nasal / $\tilde{V}\tilde{V}$ / triggers harmony, but pre-N [ $\tilde{V}\tilde{V}$ N] does not.

A second mechanism for producing abstraction in exemplar theory comes from phonetic influence between morphologically and/or semantically related forms. For example, consider the well-known case of incomplete neutralization in German (see Du and Durvasula 2025 for references and recent discussion). In German, vowels tend to be longer before voiced obstruents (e.g. Braunschweiler 1997). This effect seems to persist even when final devoicing has applied: the vowel in / $\text{ʁa:d}/ \rightarrow [\text{ʁa:t}]$  'wheel' is slightly longer, phonetically, than the vowel in / $\text{ʁa:t}/ \rightarrow [\text{ʁa:t}]$  'council'. In exemplar models, the slight lengthening of the vowel in [ $\text{ʁa:t}$ ] 'wheel' can be attributed to influence from the plural form [ $\text{ʁɛ:d-ɐ}$ ] 'wheels', where the vowel is transparently lengthened before voiced [d]. No such influence exists for [ $\text{ʁa:t}$ ] 'council', which has the plural form [ $\text{ʁɛ:t-ə}$ ] 'councils' (see also Braver 2019; Kaplan 2017).

Incomplete neutralization is a kind of phonetic opacity: singular [ $\text{ʁa:t}$ ] 'wheel' opaquely inherits the vowel length of plural [ $\text{ʁɛ:d-ɐ}$ ] 'wheels', where lengthening is phonetically transparent. (This bears a close resemblance to the generative mechanism of OUTPUT-OUTPUT FAITHFULNESS (Benua, 2000; Braver, 2019), discussed in section 5.2.2.) The question naturally arises whether connections between morphologically related forms can also be leveraged to model the opaque non-application of harmony in forms ending in [ $\tilde{V}\tilde{V}$ N].

We believe the answer is no: the requisite morphological relations are simply not present for the [ $\tilde{V}\tilde{V}$ N] items in our study. Words like [ $\text{ədʒəʋāṇ}$ ] 'omum seed' are monomorphemic roots. To force the opaque non-application of harmony in [ $\text{ədʒəʋāṇ}$ ] through phonological or phonetic connections with morphologically related forms, there must be an item like [ $\text{ədʒəʋaa}$ ], in which harmony *transparently* fails to apply, because there is no nasal vowel to trigger it. However, no such form exists, because [ $\text{ədʒəʋāṇ}$ ] is a non-decomposable root: it always ends in [ $\tilde{V}\tilde{V}$ N] on the surface. (We elaborate on this point in more detail in section 5.2.2.)

For suffixed forms in our data like [ $\text{ləɛ-jāṇ}$ ] 'take-INF.OBL', one could appeal to influence from a non-nasalized, related form of the stem vowel ([ $\text{ləɛ-jaa}$ ] 'take-IMP') to explain why harmony fails to apply in [ $\text{ləɛ-jāṇ}$ ]. However, this explanation also falls short, because it equally — and again, incorrectly — predicts that nasal harmony should be inhibited whenever a stem appears with an oral suffix in a related form. For example, [ $\text{mətʃii-ʋaa}$ ] 'fisherman' contains a suffix that lacks contrastive nasal vowels and consequently does not exhibit nasal harmony. If non-nasalized, related forms of a stem causally determine whether harmony applies, we should expect this entirely oral form to inhibit harmony in the related form [ $\text{mətʃii-jāṇ}$ ], \*[ $\text{mətʃii-jāṇ}$ ] 'fish-PLURAL'. Clearly, this is not the case, so one cannot appeal to related forms to explain the Panjabi harmony patterns.

A third potential mechanism for producing opacity in / $\text{VVG}\tilde{V}\tilde{V}\text{N}/ \rightarrow [\text{VV.G}\tilde{V}\tilde{V}\text{N}]$ , \*[ $\tilde{V}\tilde{V}.\tilde{G}\tilde{V}\tilde{V}\text{N}$ ] is to invoke influence between *phonologically* related forms. Research in exemplar theory has sometimes assumed that phonologically similar forms can influence each other, through their gestalt similarity, regardless of their morphological (non-)relatedness (e.g. Bybee 2001, p.22). Concretely, if pre-N / $\text{VVG}\tilde{V}\tilde{V}\text{N}/ \rightarrow [\text{VV.G}\tilde{V}\tilde{V}\text{N}]$  is influenced by *oral* [ $\text{VV.GVV}$ ], that influence could inhibit harmony in the penult of [ $\text{VV.G}\tilde{V}\tilde{V}\text{N}$ ], in order to maintain consistency in the nasality of the penultimate pre-glide stem vowel.

The obvious question here is why pre-N / $\text{VVG}\tilde{V}\tilde{V}\text{N}/ \rightarrow [\text{VV.G}\tilde{V}\tilde{V}\text{N}]$  should be influenced

by oral [VV.GVV], specifically. Indeed, forms with contrastive nasal vowels, [ṼṼ.ḠṼṼ], are at least equally plausible candidates for influencing pre-N [VV.GṼVN] through some notion of overall phonological similarity. Privileging oral [VV.GVV] for this role is not well-motivated. Furthermore, it simply sneaks covert underlying representations in through the back door, by implicitly admitting that pre-N /VVGVVN/ → [VV.GṼVN] is in some sense more closely related to oral [VV.GVV] than to contrastively nasal [ṼṼ.ḠṼṼ] (see also McCarthy 1999 on sympathy theory).

Fourth, it is possible that the distinction between pre-N /VVGVVN/ → [VV.GṼVN] and contrastive [ṼṼ.ḠṼṼ] is simply an artifact of historical change. Presumably, pre-N assimilation developed *after* the emergence of nasal harmony, thus yielding an opaque synchronic interaction between the two processes. Speakers might simply memorize forms like [mətʃĩ-ḡḡ] ‘fish-PLURAL’ vs. [lɛɛ-jḡḡ] ‘take-INF.OBL’. This would absolve the theory of any need to model the interaction between nasal harmony and local nasal assimilation.

The problem with this analysis is a familiar one: it fails to account for the productivity and generality of both nasal harmony and local nasal assimilation. As far as we are aware, these are completely regular processes in the varieties of Panjabi analyzed here. Through informal wug testing carried out with two native Panjabi speakers (Muhammad Riaz and Amir Adkuokhar), novel forms mirroring the structure of the Panjabi words in Experiment 2 impressionistically follow the same nasality patterns found in real Panjabi words in this paper: contrastive nasal vowels trigger harmony (hypothetical singular [p<sup>h</sup>ii] vs. plural [p<sup>h</sup>ĩ-ḡḡ]), but pre-N vowels do not (hypothetical [p<sup>h</sup>iivḡḡ]). In addition, Gorman (2013) notes that some patterns that are statistically robust in the lexicon may go unlearned by speakers, particularly when they are not supported by corresponding alternations. Nevertheless, Panjabi pre-N forms do not fall into this category, as evidenced by the productive application of pre-N nasalization to underlying oral vowels followed by a nasal suffix (e.g., [veejḡḡ-ḡ] ‘to marry-NOML’) in section 5.1. It is also telling that, as far as we are aware, there are **zero** exceptions to either the rule that nasalizes pre-N vowels or the optional harmony rule (apart from systematic opaque interaction). Thus, we feel confident in assuming that the differences between these two nasal vowels would evince the same phonological behavior even when produced in completely novel forms. Something must ensure this; simple rote memorization will not do the job.

Lastly, the patterns of nasal harmony described in this paper could be accounted for with a more complex co-occurrence restriction on nasality, \*[ḠṼVN], which bans a nasalized glide before a nasalized (long) vowel, followed by a nasal consonant. The trigram constraint \*[ḠṼVN] straightforwardly excludes unattested \*[ṼṼḠṼVN] sequences while allowing [ṼṼḠṼṼ]. Furthermore, it does so with reference to surface forms alone: this renders the lack of \*[ṼṼḠṼVN] sequences transparent, rather than opaque, and thus vitiates the motivation for abstract underlying representations. Within an exemplar-theoretic framework — and likewise within symbolic theories that reject abstract URs not faithfully realized in some surface form (e.g., Albright 2002) — a trigram constraint like \*[ḠṼVN] could plausibly emerge from distributional learning over the Panjabi lexicon, based on surface forms alone.

However, two central issues have been raised in the literature concerning the viability of such complex co-occurrence constraints. The first is computational: the cost of learning featural constraints over segment-sized sequences quickly becomes intractable as the length of those sequences increases (Hayes and Wilson, 2008, 391-2). Constraints are stated over windows of length *n*, where *n* is some number of segments or other symbols (e.g. \*[g#], \*[VtV], etc.). As *n* increases, the

hypothesis space of possible constraints expands exponentially (the exact rate of growth depends on how many natural classes constraints may refer to). This makes it increasingly difficult for a learner to efficiently navigate the constraint space as constraints expand their segmental scope.<sup>15</sup> For example, Hayes and Wilson (2008) argue that constraints on segment combinations must generally be limited to  $n = 2$ ; they relax this to  $n = 3$  for constraints which refer only to the major class features [syllabic], [consonantal], and [sonorant]. The constraint \*[ $\tilde{G}\tilde{V}\tilde{V}N$ ] of course goes beyond these limitations.

Moreover, while learning *segmental* co-occurrence restrictions is computationally straightforward once a maximum window size,  $n$ , is fixed (Heinz, 2010b), there are independent reasons to believe that phonotactic learning must operate over featural representations rather than purely segmental ones (e.g., Halle, 1978b; Linzen and Gallagher, 2017). For example, Wilson and Gallagher (2018) argue that feature-based constraints are necessary for learners to generalize from frequent segments to infrequent members of the same natural class. Without such generalization, accidental gaps involving rare segments may be incorrectly learned as principled phonological restrictions. However, moving from segments to features substantially enlarges the hypothesis space because learners must consider a vastly larger set of possible natural classes. As Heinz (2010a, p.652) notes, “...grammars stated over featural representations dramatically increase the learner’s search space because there are many more natural classes than segments, potentially making it difficult to make efficient computations”. While several recent approaches have proposed ways of structuring the hypothesis space to improve search efficiency (e.g., Chandlee et al., 2019; Rawski, 2021; Swanson et al., 2026), the general challenge remains that constraints referring to increasingly large sequences of featural representations are difficult to learn.

The second, and perhaps more pressing concern is empirical. Allowing the learner to posit highly specific co-occurrence restrictions based solely on attested patterns in the lexicon can give rise to difficulties in distinguishing between principled phonotactic gaps and accidental ones (Chomsky and Halle, 1965; Hayes and White, 2013; Swanson et al., 2026; Wilson and Gallagher, 2018). Principled gaps are those which native speakers judge to be ill-formed, whereas accidental gaps are unattested but fully acceptable to speakers. Because accidental gaps and principled gaps based on genuine phonotactic restrictions both appear as absences in the lexicon, a learner must have some mechanism for determining which generalizations should be encoded in the grammar. Without such a mechanism, learners may incorrectly promote accidental gaps to the status of phonological restrictions.

To test the extent to which such overfitting might occur in Panjabi, we examined phonotactic patterns in the Pakistani Panjabi corpus, *pnbTenTen* (Jakubíček et al., 2013), a 2.8 million-word corpus compiled in 2017 from 5,351 webpages written in Shahmukhi, the standard orthography for

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<sup>15</sup>Strictly speaking, exponential growth of the constraint space is limited to learning algorithms which exhaustively consider the space of all possible constraints. Some learners, such as BUFIA, perform a structured, partial search of the constraint space instead, and are thus sub-exponential in their worst case complexity (Rawski 2021, 53, Swanson et al. 2026).

Still, even for structured search algorithms, increasing the number of segments that constraints may refer to can nonetheless lead to dramatic changes in practical runtime (i.e. ‘sub-exponential’ does not necessarily mean ‘efficient under all conditions’; see e.g. Dean 2021). By way of illustration, we ran the BUFIA algorithm on the MALARKY data set provided at <https://github.com/pterodactylogan/bufia/>. This data set uses 20 features to describe 1800 word forms of 3-8 segments in length, with a phone inventory of 29 segments (plus a word boundary symbol). Running BUFIA on this data set with a window size of 2 segments took about 2 minutes; running it with a window size of 3 segments did not complete, as the computer ran out of available RAM after 5 hours.

Pakistani Panjabi. The corpus contains approximately 100,000 unique words of varying frequencies. Using a custom Python script, we extracted the set of 3-gram sequences absent from the corpus by determining the complete set of unique Shahmukhi characters in the corpus and transliterating those characters into their corresponding natural class category: nasal consonant (N), liquid (L), obstruent (O), long oral vowel (VV), or long nasal vowel (ṼṼ). Several complications involved in transliterating Shahmukhi to broad natural classes led us to exclude glides and short vowels from the analysis. First, Shahmukhi is a partial abjad, meaning that short vowels are written using optional diacritics, which are generally omitted from everyday writing and inferred from context. As a result, consistent transliteration of short vowels is not possible. For example, the conjunction [pər] ‘but, yet’ is most often written with two characters in Shahmukhi, omitting the short vowel: ੜੜ. Our script transliterated this word as <#pr#>, with no short vowel. Furthermore, glides in Shahmukhi are not represented by a unique orthographic symbol but are instead written with the same symbol as their corresponding vowel. For example, ੜ may represent /j/ or /i:/ and ੜ may represent /v/, /u:/, /o:/, or /ɔ:/ . The exact context for each symbol-to-sound mapping is complex and not well documented for Shahmukhi. Consequently, we chose to transcribe these symbols consistently as vowels. Given these constraints, our analysis of the corpus does not accurately analyze potential phonotactic 3-gram sequence gaps containing glides, short vowels, or vowel hiatus. Thus, our search for phonotactic gaps is limited to 3-gram sequences containing individual long vowels and non-glide consonants.

After transliterating the corpus into broad natural classes, we generated all possible 3-gram sequences for the five target natural classes mentioned above and extracted the set of unattested sequences. As expected, many missing sequences reflect principled phonotactic restrictions – e.g. the absence of [#NN] sequences, which reflects an illicit word-initial consonant cluster of two nasals. However, other gaps are less easily explained. One particularly striking case is the complete absence of [LṼṼL] sequences (liquid–nasal vowel–liquid). Panjabi readily allows [LVVL] sequences with oral vowels – for example, [lɑɑl] ‘red, ruby’ appears 634 times in the corpus. Additionally, two native speaker consultants (Muhammad Riaz and Amir Adkuokhar) independently provided judgements of well-formedness for [LṼṼL] forms, indicating — when asked whether a word like lāṁl could be a Panjabi word — that it is fully acceptable, though unattested. Moreover, smaller bigram [LṼṼ] (type frequency 1,602, 3% of words) and [ṼṼL] (type frequency 8, .01% of words) sequences are attested in the corpus, so less complex constraints based on simpler bigram co-occurrence restrictions cannot account for the gap. Another example is the absence of [ṼṼLṼṼ]. Given that [VVLVV] sequences are extremely common (type frequency 7,134, 11.6% of words), and that nasal vowels separated by other consonants are attested (e.g., type frequency of 7 for [ṼṼOṼṼ], .01% of words), this gap likewise appears to be accidental rather than principled.

While the phonotactic analysis here provides an illustration of how permitting complex co-occurrence constraints can lead to the grammatical prohibition of accidental gaps, previous work has demonstrated that this is a general issue for any approach that permits these types of constraints (Chomsky and Halle, 1968; Hayes and White, 2013; Wilson and Gallagher, 2018). In any case, the analysis here shows that a statistical learner limited to making generalizations over observed forms might posit a constraint like \*[LṼṼL] or \*[ṼṼLṼṼ] simply because no such sequence occurs in the lexicon. This is clearly an undesirable outcome – an example of a complex co-occurrence constraint banning a form that is well-formed for native speakers, despite its absence. While it is theoretically possible to model Panjabi’s nasal harmony patterns using surface-based

generalizations alone, doing so comes at a significant cost. The computational demands of learning high-order co-occurrence restrictions are substantial, and, more importantly, this approach runs the risk of overfitting the lexicon, thereby failing to distinguish between accidental and principled gaps and resulting in the mischaracterization of speakers’ phonological competence.

In sum, in order to model the Panjabi data presented here, exemplar theory must be augmented with some mechanism(s) that allow speakers to arrive at covert underlying representations. We believe this is a matter of principle, rather than a consequence of the particular assumptions discussed above: it follows, more or less logically, from the surface-oriented character of all contemporary versions of exemplar theory.

### 5.2.2 Opacity in surface-oriented generative models

In the generative tradition, it has sometimes been suggested that underlying representations can be dispensed with entirely, their functions being subsumed by surface-to-surface relationships between morphologically related surface allomorphs, or other purely surface-oriented generalizations (e.g. Albright 2002; Allen and Becker 2015; Burzio 1996; Cole and Hualde 2011; Hayes 1999; Scobbie et al. 1996; Wang and Hayes 2025, and various others; cf. Bermúdez-Otero 2018; Bowers 2015; Hyman 2018; Krämer 2012 and references there). We illustrate with a case of counterfeeding opacity in Berbice Dutch Creole (Dow, 2014).

In Berbice Dutch Creole, nasal consonants generally assimilate in place of articulation to following oral stops (e.g., [kamba] ‘drum’ and [juŋgu] ‘young’). Additionally, stem-final vowels may delete when followed by a suffix. These two processes interact opaquely, in a counterfeeding relationship, as can be seen from derivations like /nimi-tɛ/ → [nim-tɛ] ‘know-ANTERIOR’ (6).

#### (6) Counterfeeding opacity in Berbice Dutch Creole

|                     |                                                   |           |
|---------------------|---------------------------------------------------|-----------|
|                     |                                                   | /nimi-tɛ/ |
| Place assimilation: | C[+NASAL] → [αPL]/__ [αPL,-CONT,-SON]             | –         |
| Vowel deletion:     | V → ∅/ __ ] <sub>STEM</sub> – <sub>SUFFIX</sub> [ | [nim-tɛ]  |
|                     |                                                   | [nim-tɛ]  |

As in the rule-based analysis of Panjabi nasal harmony (5), the rule-based analysis of Berbice Dutch Creole hinges on a distinction between underlying /N/+stop clusters (which undergo place assimilation), and derived /N/+stop clusters (which do not assimilate).<sup>16</sup>

An alternative, surface-oriented analysis of these facts is also possible, which does not make crucial reference to underlying representations. Following Benua (2000), we may assume that OUTPUT-OUTPUT FAITHFULNESS constraints enforce similarity between morphological bases and complex forms built on those bases. OO-FAITH constraints evaluate similarity along specific phonological dimensions: the constraint OO-IDENT-PLACE (7b) specifically bans changes in place of articulation between a morphological base like [nimi] and a corresponding inflected form like [nim-tɛ] (7). Importantly, OO-FAITH constraints refer only to the *surface* forms of bases and their morphological derivatives.

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<sup>16</sup>The Berbice Dutch Creole facts are more nuanced than the text here implies. For example, nasal place assimilation is in fact optional in forms like [nim-tɛ]~[nin-tɛ] ‘know-ANTERIOR’, and stem-final vowel deletion shows evidence of morphological idiosyncrasy. We present a simplified version of the Berbice Dutch Creole data for expository purposes; see Dow (2014) for more details.

The simplified tableau in (7c) shows how output-oriented faithfulness relations can produce counterfeeding opacity without drawing a distinction between underlying and derived forms. In short, the regular process of nasal place assimilation is inhibited in [nim-tɛ] because it would produce a phonological discrepancy between the base [nimi] and the derived form \*[nin-tɛ]. The input to phonological evaluation is a concatenation of independently observed surface allomorphs, [nimi] and [-tɛ], rather than an abstract UR.

(7) Counterfeeding opacity in Berbice Dutch Creole as output-oriented faithfulness

- a. NT PLACE ASSIMILATION: assign one violation for every nasal consonant followed by an oral stop, such that the nasal and stop differ in their place of articulation.
- b. OO-IDENT-PLACE: assign one violation for every morphologically complex form  $\mathbb{B}$ - $\mathbb{A}$ , where  $\mathbb{B}$  is a morphological base and  $\mathbb{A}$  an affix, in which the  $\mathbb{B}$  substring of  $\mathbb{B}$ - $\mathbb{A}$  contains a segment which differs in place of articulation from the corresponding segment in the base form  $\mathbb{B}$ .

|    | [nimi-tɛ] / BASE: [nimi] | OO-IDENT-PLACE | NT PLACE ASSIMILATION |
|----|--------------------------|----------------|-----------------------|
| c. | a. nin-tɛ                | *! W           | L                     |
|    | b. nim-tɛ                |                | *                     |

However, it is well-known that output-oriented faithfulness does not provide a general analysis of phonological opacity (e.g. Bermúdez-Otero 2011; Mascaró 2016; Trommer 2013; Wolf 2008). OO-FAITH constraints can only produce opacity in morphologically complex forms, by demanding that phonological similarity to a morphological base take precedence over general phonotactic constraints (7).

In morphologically simple forms — that is, roots — there is no base to be faithful to, and thus no mechanism for generating opacity. This is precisely the situation presented by the opaque non-application of nasal harmony in forms like [dʒəvũãɲ], \*[dʒəũãɲ] ‘youth, soldier’ in Panjabi. The root [dʒəvũãɲ] has no morphological base to be faithful to; hence, output-oriented mechanisms for producing opacity fall short of explaining why [dʒəvũãɲ] fails to undergo harmony. This ‘missing base’ problem is not specific to OO-FAITH: it generalizes to all phonological theories which attempt to generate opaque phonological interactions by means of surface relationships between morphologically related forms.

A conceptually distinct, surface-oriented approach to opacity in nasal spreading is provided by OPTIMAL DOMAINS THEORY (ODT) (Cole and Kisseberth 1994, 1995). Briefly summarizing, in ODT, harmony domains are specified in surface, output forms. Surface-oriented constraints require all segments in a harmony domain to share the same value for a particular feature. The distributions of harmony domains themselves are also specified by surface-oriented constraints.

Cole and Kisseberth (1995) provide an analysis of nasal harmony in Máíhĩki (formerly, Orejón) which is strikingly similar to the pattern of nasal harmony we describe for Panjabi (though see Sylak-Glassman et al. 2014 for a different description of the core facts). Nasality spreads rightward from nasal vowels in the initial syllable, the only position in which vowel nasality is contrastive. Harmony may spread through the glide [j], which we assume is nasalized, following Cole and Kisseberth (1995). Harmony is illustrated in (8a), in which we indicate nasal harmony domains by means of parentheses.

(8) Nasal harmony in Máihĩki

- a. Long-distance rightward nasal spreading from contrastive / $\tilde{V}$ /:  
/sěje/ → (sějẽ) ‘species of bird’
- b. Only local rightward nasal spreading from nasal consonants:  
/naji/ → (nã)ji ‘grandson’

However, words beginning in a nasal stop show only local nasalization of the following vowel, without longer-distance harmony (8b).<sup>17</sup> Cole and Kisseberth (1995) analyze this contrast by assuming that contrastively nasal vowels initiate harmony domains that must spread as far to the right as possible (8a), while nasal consonants initiate harmony domains that only need spread as far as the rightmost syllable boundary (8b).

Crucially, Cole and Kisseberth (1995) must *also* invoke covert underlying representations for this analysis to function as intended. Roots like [nãji] ‘grandson’ are non-alternating: they are always realized with an initial nasal vowel. Lexical representations like /nãji/, which are faithful to the invariant surface realization [nãji], incorrectly predict nasal harmony in [nãji], \*[nãjĩ] on analogy with [sějẽ], in which nasal harmony is initiated by an underlying nasal vowel (8a). The only tractable lexical representation for ‘grandson’ must therefore be the abstract, covert UR /naji/ — despite the fact that this morpheme never surfaces as such (i.e. the initial vowel is always nasal on the surface). We conclude that optimal domains theory also requires covert underlying representations.

A similar surface-oriented analysis might be developed from perceptually grounded theories of harmony, such as the motivation behind weak triggers of harmony outlined in Walker (2005, 2014). Under this analysis, contrastive nasal / $\tilde{V}\tilde{V}$ / vowels in Panjabi might be treated as weakly cued triggers: because nasality is realized only on the vowel, harmony is employed to enhance the perceptual recoverability of the nasal feature by extending it across additional vowels and glides. Pre-N vowels, on the other hand, occur adjacent to a nasal consonant, which buttresses the percept of the pre-N vowel’s nasality with an additional, highly salient nasal cue, as compared to contrastive nasal / $\tilde{V}\tilde{V}$ / vowels that lack such a salient cue to vowel nasality. Harmony is therefore unnecessary in pre-N [ $\tilde{V}\tilde{V}$ N] forms under this view because nasality cues are sufficiently salient on the nasal consonant without it. Local vowel nasalization could help cue consonant nasality, but further spreading is not necessary.

While such an analysis is conceptually distinct from ODT, it encounters the same representational quandary. Speakers must still distinguish nasal vowels with contrastive nasality from nasal vowels with predictable nasality adjacent to a nasal consonant. This distinction is not available from the surface phonetic realization of the vowels alone, since they are statistically equivalent. Thus, a weak-trigger analysis cannot eliminate the need for a representational distinction between the two vowel types. If pre-N [ $\tilde{V}\tilde{V}$ N] vowels are represented simply as nasal vowels, nothing prevents them from patterning with contrastive nasal vowels as harmony triggers. Conversely, if they are exempted from triggering harmony because their nasality is treated as distinct in some way, then speakers must encode precisely this distinction. Since we have gone to great lengths to

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<sup>17</sup>Sylak-Glassman et al. (2014) argue that vowels following a nasal consonant are realized as oral rather than nasal in Máihĩki. Under their phonetic analysis, the specific representational problem would dissolve. Regardless of the ongoing phonetic debate regarding the realization of Máihĩki post-nasal vowels, the pattern the example typifies — where surface neutralization renders an underlying representation opaque — requires covert URs.

show that the two vowel types are statistically equivalent in their realization of nasality, we argue that distinction cannot be read directly from the surface signal.

### 5.2.3 Learning Covert URs

A major objection to permitting abstract URs in linguistic analysis is the challenge they pose for acquisition. Specifically, if abstract URs are considered, the space of potential URs a learner must evaluate grows substantially.

Instead of rejecting abstract URs due to this concern, a substantial body of research has proposed strategies to mitigate the complexity of UR learning. For instance, Tesar (2014, 2016) shows that the space of potential URs need not be searched exhaustively if it is efficiently organized in such a way that allows broad swaths of implausible URs to be ruled out in one fell swoop (see also Chandlee et al. 2019; Rawski 2021; Yolyan 2025 for similar perspectives). In addition, several approaches (e.g. Abbott 1985; O’Hara 2017; Paramore 2025, 2026b; Pater et al. 2012; Rasin and Katzir 2018) offer distinct mechanisms for minimizing abstraction in UR learning while still permitting abstract URs, at least in principle. We refer interested readers to these works and the references therein for further discussion of the learnability of abstract URs, and in particular covert URs of the sort defended here.

Our results also bear on the role of lexicon optimization in the learning of underlying forms (e.g. Prince and Smolensky 2004). Lexicon optimization amounts to the proposal that, in the absence of alternations, learners will assume that a non-alternating surface segment [X] has the corresponding underlying form /X/. Under this assumption, Panjabi learners should assume underlying nasal vowels / $\tilde{V}\tilde{V}N$ / for non-alternating pre-N vowels in [ $\tilde{V}\tilde{V}N$ ]. We have argued that this is incorrect: surface [ $\tilde{V}\tilde{V}N$ ] is systematically analyzed as underlying /VVN/, even in the absence of alternations (see also McCarthy 2005b, Nevins and Vaux 2007, Krämer 2012, Rasin and Katzir 2016, 2018).

Assuming our results are representative of the Panjabi lexicon as whole, it would seem that Panjabi learners are not only *capable* of positing URs stripped of redundant information, they *always* posit such URs, at least in the case of [ $\tilde{V}\tilde{V}N$ ]  $\leftarrow$  /VVN/. If /VVG $\tilde{V}\tilde{V}N$ / were a potential underlying form, we would expect to see at least some cases of pre-N vowels triggering harmony in \*[ $\tilde{V}\tilde{V}G\tilde{V}\tilde{V}N$ ]; the absence of such examples seems telling.

It could be that underlying / $\tilde{V}\tilde{V}N$ / is disallowed in Panjabi as the result of a morpheme structure constraint (MSC) on underlying forms (e.g. Booij 2011), a view that rejects Richness of the Base (RotB). Alternatively, Panjabi learners might adopt a learning strategy that systematically rejects / $\tilde{V}\tilde{V}N$ / as a string in *actual* URs, without directly banning underlying / $\tilde{V}\tilde{V}N$ / by means of a MSC (see also Stampe 1973, McCarthy 1998). Under the latter view, rejecting / $\tilde{V}\tilde{V}N$ / as the stored UR of any Panjabi morpheme does not conflict with RotB, which concerns the set of possible *inputs* — both stored and unstored — to the grammar. RotB requires that the grammar be able to map hypothetical / $\tilde{V}\tilde{V}N$ / inputs to surface forms, but it does not require that learners assign such forms as URs in the lexicon. It is difficult to see how these competing analyses could be teased apart empirically, and the potential conclusions are beyond the scope of this paper. As such, we leave the debate to future research.

## 6 Conclusion

We have presented original phonetic data from Panjabi to establish the novel descriptive generalization that nasal harmony interacts opaquely with local nasal assimilation in /VVN/ sequences. We have further argued that modeling this opaque interaction requires reference to abstract underlying forms that never phonetically surface — forms we dub *covert URs*.

Covert URs allow for a straightforward distinction between underlying nasal vowels (which trigger harmony) and phonologically derived nasal vowels (which do not). Drawing this distinction *without* covert URs proves difficult. Many pre-N vowels in /VVN/ → [ṼṼN] sequences are in non-alternating roots and affixes. This means that the vowels in question are *always* nasal [ṼṼN] on the surface. The lack of alternations in nasality presents a challenge for distinguishing non-alternating, contrastive nasal vowels /ṼṼ/ (which are unpredictably nasal) from non-alternating, derived nasal vowels [ṼṼN] (which are predictably nasal) by reference to surface forms alone.

We are broadly sympathetic to the goals of exemplar theory, and the empirical findings that motivate exemplar theory and related frameworks. The question is not whether surface-oriented models of phonological computation are justified; the question is whether they are *sufficient*. We contend that an adequate theory of phonology will require mechanisms for learners to arrive at abstract lexical representations that depart from observed surface forms in filtering out at least some surface-predictable information. This conclusion, while traditional, strikes us as surprising in a modern context in which grammatical abstraction has been downplayed in favor of sophisticated, surface-oriented models of phonological learning and generalization.

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## 7 Appendix

### 7.1 Experimental items

| Condition 1 - CVV |                        | Condition 2 - C $\tilde{V}\tilde{V}$ |                   | Condition 3 - CVVN  |                         |
|-------------------|------------------------|--------------------------------------|-------------------|---------------------|-------------------------|
| baat              | ‘story’                | bāā                                  | ‘arm’             | paan                | ‘Betel nut chewing’     |
| bii               | ‘seed’                 | bāāk                                 | ‘early teen’      | biin                | ‘a musical instrument’  |
| boo               | ‘smell’                |                                      |                   |                     |                         |
| piid              | ‘pain’                 | pīīg                                 | ‘swing’           |                     |                         |
| poo               | ‘12th Panjabi month’   | pōōtʃ                                | ‘arrival’         | koon                | ‘who’                   |
| daa               | ‘strategy (wrestling)’ |                                      |                   | daam                | ‘price, money’          |
| daak              | ‘post’                 | dāāg                                 | ‘big stick’       |                     |                         |
| deed              | ‘one and a half’       |                                      |                   |                     |                         |
| doo               | ‘two’                  |                                      |                   | doon                | ‘ropes on a knit bed’   |
| dzii              | ‘family member’        |                                      |                   |                     |                         |
|                   |                        | d3ōō                                 | ‘barley’          |                     |                         |
| d3oog             | ‘coming together’      | d3ōōk                                | ‘leach’           |                     |                         |
|                   |                        | d3ūū                                 | ‘louse’           | d3uun               | ‘June’                  |
| taa               | ‘warmth, fever’        | tāā                                  | ‘that; so that’   | taan                | ‘melody’                |
| t <sup>h</sup> aa | ‘COP.PST’              | t <sup>h</sup> āā                    | ‘place, room’     | t <sup>h</sup> aan  | ‘bolt of cloth’         |
| tōk               | ‘yoke, iron collar’    |                                      |                   | tōn                 | ‘neck’                  |
| tʃaa              | ‘desire, wish’         | tʃ <sup>h</sup> āā                   | ‘shade’           | tʃ <sup>h</sup> aan | ‘non-refined flour’     |
| ruup              | ‘beauty’               | rūū                                  | ‘cotton’          | luun                | ‘salt’                  |
| saa               | ‘breath’               |                                      |                   |                     |                         |
| seek              | ‘warmth’               | sēēk                                 | ‘termite’         |                     |                         |
| sii               | ‘sew.IMP’              |                                      |                   | siin                | ‘ploughing’             |
| sō                | ‘hundred’              | sōō                                  | ‘sleep.IMP’       | sōn                 | ‘rainy season’          |
| suud              | ‘profit, interest’     | tūū                                  | ‘you’             |                     |                         |
|                   |                        | vāāg                                 | ‘like, similar’   | vaan                | ‘strings of a knit bed’ |
| gaal              | ‘abuse’                | gāā                                  | ‘cow’             |                     |                         |
| kaad3             | ‘button-hole’          | kāā                                  | ‘crow’            | k <sup>h</sup> áán  | ‘a proverb’             |
| kuuk              | ‘melodious sound’      | kūūd3                                | ‘black sparrow’   |                     |                         |
| k <sup>h</sup> uu | ‘a well’               | k <sup>h</sup> ūūd3                  | ‘a corner, angle’ | xuun                | ‘blood’                 |
| xaab              | ‘dream’                |                                      |                   | xaantʃaa            | ‘corner, trick’         |

Table A1: Experiment 1 tokens, consisting of 63 monomorphemic words separated into three groups: oral vowels (CVV), nasal vowels (C $\tilde{V}\tilde{V}$ ), and /VVN/ vowels (CVVN).

| oral [VG̃V]                                    |                  |                        |                         |
|------------------------------------------------|------------------|------------------------|-------------------------|
| sət-aqjii                                      | seven-twenty     | ɔɔlii-jaa              | pious man-PL            |
| həvaa                                          | air              | tʃoo-vii               | four-twenty             |
| paavee                                         | cot leg          | beevaa                 | a widow                 |
| dəvaa                                          | medicine, remedy | taavuu                 | father's oldest brother |
| mʊk <sup>h</sup> iijaa                         | chief            | vək <sup>h</sup> aavee | boasting                |
| Nasal Conditions - [ṼG̃Ṽ=CV] and [ṼG̃Ṽ=NV] |                  |                        |                         |
| tʃãũvẽẽ                                        | pumicestone      | ũũ-vẽẽ                 | that-way                |
| dõõ-vãã                                        | two-way          | kii-ũẽẽ                | what-way                |
| ẽẽ-ũẽẽ                                         | this-way         | mətʃiĩ-jãã             | fish-PL                 |
| sãã-ũãã                                        | breath-PL        | tiiũii                 | a woman, wife           |
| pre-N [VG̃VN]                                  |                  |                        |                         |
| dʒəvããŋ                                        | youth, soldier   | ədʒəvããŋ               | omum seed               |
| siijããŋ                                        | recognition      | teejããŋ                | attention               |
| lɛɛ-jããŋ                                       | take-INF.OBL     | aavããm                 | general public          |

Table A2: Experiment 2 tokens, consisting of 24 di- and trisyllabic words separated into three groups: oral [VG̃V], contrastive nasal /ṼṼ/, and pre-N vowels /VVN/.

## 7.2 Annotation Procedure & Excrescent nasals

The first author and two undergraduate research assistants completed the annotations. The first author verified the quality of all annotations. Boundaries between oral consonants and vowels were marked at the onset/offset of high amplitude in the oral channel, along with the onset of increased formant activity in the spectrogram. The boundary between vowels and the onset of nasal consonants was marked at the attenuation of higher formant activity coupled with a rapid decline in waveform amplitude in the oral channel. A sample annotation is provided in Figure A1.

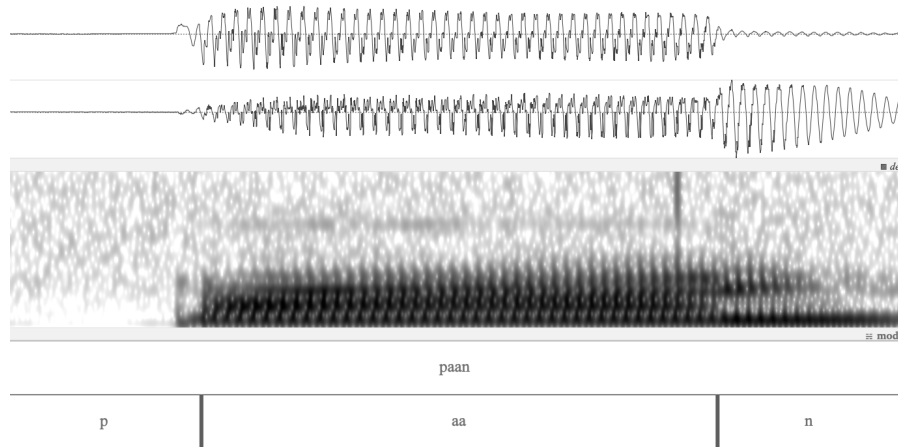


Figure A1: Spectrogram and waveform showing a sample annotation for /paan/ for speaker AR0. The top waveform shows amplitude for the oral channel, and the bottom waveform shows amplitude for the nasal channel.

For almost all of the  $C\tilde{V}\tilde{V}$  tokens with oral stops in the coda position, oral occlusion for the coda consonant was achieved before the offset of articulation of nasality for the  $/\tilde{V}\tilde{V}/$  vowel. This resulted in the physical presence of an intrusive nasal stop for a short period between the gestures of the vowel and the coda (see e.g., Bennett et.al. to appear; Desmeules-Trudel and Brunelle 2018; Lapierre 2023). Due to the minimal amount of oral air expelled during the production of nasal consonants, nasality increased rapidly at the offset of the contrastive nasal  $/\tilde{V}\tilde{V}/$  vowel when these intrusive nasal consonants were present. To avoid corrupting the reported nasality of the  $/\tilde{V}\tilde{V}/$  vowel, intrusive nasals were annotated as part of the consonant segment whenever present. Importantly, it is clear from other phonotactic restrictions in Panjabi that this nasal stop is indeed intrusive and not present in the phonology. Specifically, Bhatia (1993) reports that NC coda clusters are illicit in the language when following a long vowel. A representative example of these intrusive nasal consonants is evidenced by the spectrogram and waveform in Figure A2.

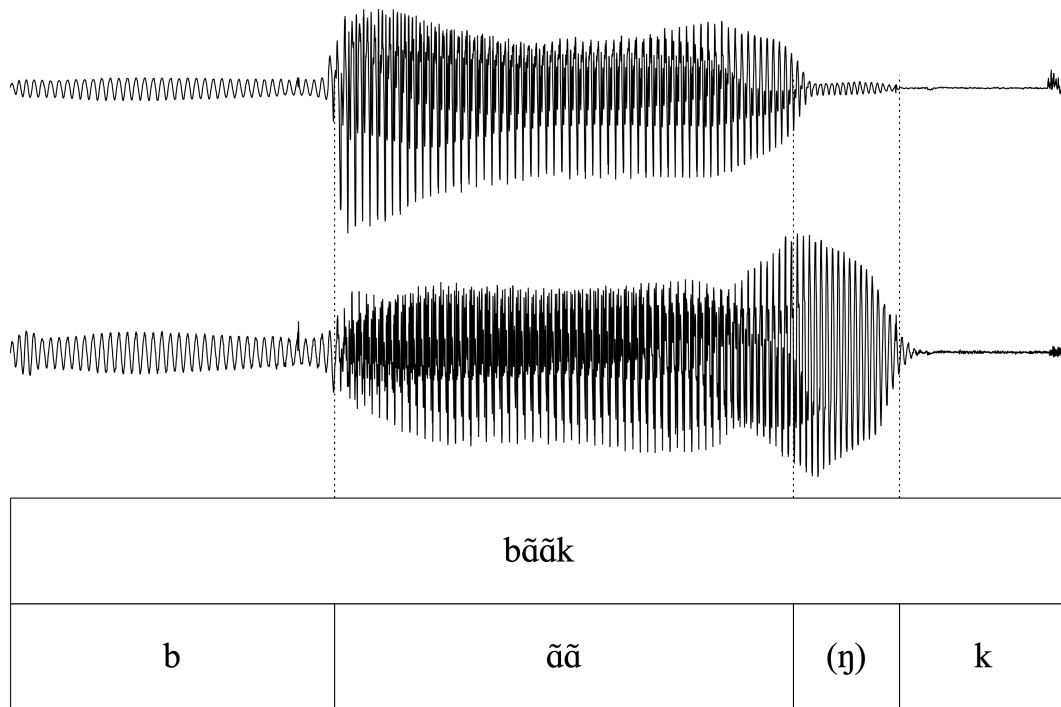


Figure A2: Waveforms showing the intrusive  $[\eta]$  in  $/bāṁk/$  for speaker AK2. The top and bottom waveforms correspond to the oral and nasal channels respectively.

### 7.3 Acoustic Analysis of F1 modulation

It has been reported that both contrastive and allophonic nasal vowels may have different F1 values than oral vowels of the same quality (e.g. Carignan 2017; Carignan et al. 2011; Shosted et al. 2012 and references therein). To assess this possibility, we measured formant values in our air pressure recordings from Experiment 1 using a Python implementation of FASTTRACK (Barreda, 2021), and then normalized the resulting values with log-additive regression normalization (Barreda and Nearey, 2018). Mean normalized F1 values for the middle 10% of vowels are provided in Figure A3.

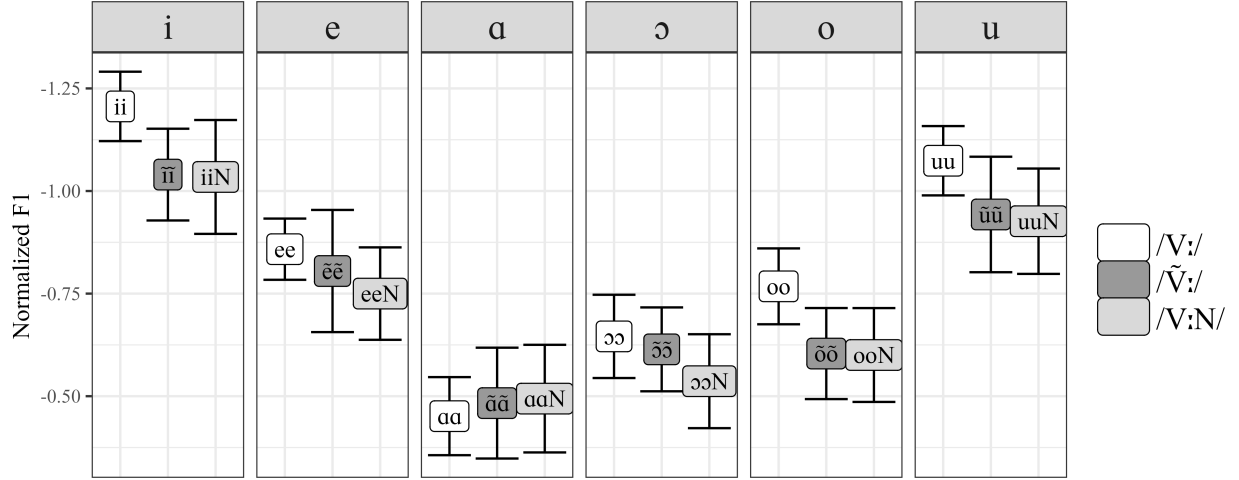


Figure A3: Mean normalized F1 values at middle 10% of each vowel. Error bars show  $\pm 0.5$  standard deviation.

Consistent with previous findings for nasal vowels, allophonically nasalized /VVN/ and contrastive nasal /ṼṼ/ seem to be systematically lower than their oral counterparts (or slightly raised, in the case of low /aa āā aaN/).<sup>18</sup>

Importantly, F1 values for /VVN/ and /ṼṼ/ pattern together, as expected if the vowels are [+NASAL] in both cases. Although allophonically nasalized /eeN/ and /ɔɔN/ might appear to be somewhat lower than contrastively nasalized /ẽẽ õõ/ in Figure A3, a statistical analysis failed to detect any reliable difference in F1 between allophonically nasalized /VVN/ and contrastively nasalized /ṼṼ/, for any vowel quality. We fit a linear mixed effects model to normalized F1 at vowel midpoint for tokens of allophonically nasal /VVN/ and contrastively nasal /ṼṼ/, using the formula in (9a), the setting REML=F, and the LME4 and LMERTEST packages (Bates et al., 2024; Kuznetsova et al., 2020). Vowel duration was centered and scaled.

- (9) a. INITIAL MODEL: F1 (normalized) ~  
V quality \* Nasality (/VVN/ vs. /ṼṼ/) + V quality \* V duration +  
(1|Word) + (1+Nasality|Speaker)
- b. FINAL MODEL: F1 (normalized) ~  
V quality \* V duration + (1|Word) + (1+Nasality|Speaker)

We then carried out stepwise simplification of fixed effects using the PERFORMANCE package (Lüdtke et al., 2021) to compare nested models using the log-likelihood test. We omitted variables one at a time, dropping the variable which explained the least variance at each step, and retaining simple predictors whenever they participated in a higher-order interaction. Our criterion for inclusion in the model was  $\alpha < .1$ . This led to the omission of the V QUALITY:NASALITY interaction ( $p = .21$ ), and then NASALITY ( $p = .65$ ). The V QUALITY:DURATION interaction was retained ( $p = .01$ ), which ended model simplification. The residuals in this final, reduced model (9b) appeared approximately normally distributed.

<sup>18</sup>Pairwise  $t$ -tests with  $\alpha = .05$  suggest that F1 for contrastive oral /VV/ vowels is significantly different from F1 for both allophonic /VVN/ and contrastive /ṼṼ/ nasal vowels, with the exception of contrastive /ẽẽ õõ/ vs. oral /ee ɔɔ/. Since F1 as such is not the focus of our analysis, we omit more detailed statistical exploration.

These results imply that F1 variation among nasal vowels is related to vowel quality and duration (section 4.3), but is not affected by the source of vowel nasality (allophonic vs. contrastive). This is similar to the findings of Zahid and Hussain (2012) that A1-P0 and A1-P1 measurements (which are indices of nasality) do not significantly differ for contrastive nasal / $\tilde{V}\tilde{V}$ / vs. allophonic nasal /VVN/ in Panjabi (section 2). Jointly, these results are consistent with our claim that allophonic vowel nasalization in /VVN/  $\rightarrow$  [ $\tilde{V}\tilde{V}$ N] is neutralizing with contrastive / $\tilde{V}\tilde{V}$ /, producing statistically equivalent and phonologically [+NASAL] vowels.

It is of course possible that other acoustic parameters associated with nasality might differ between / $\tilde{V}\tilde{V}$ / and /VVN/ in Panjabi (e.g. breathiness, F1 bandwidth, dynamic changes in F1 over time, F2, etc.; see e.g. Carignan 2017; Shosted et al. 2012; Styler 2017). However, exhaustively analyzing all of the potential acoustic differences between / $\tilde{V}\tilde{V}$ / and /VVN/ is beyond the scope of the present paper. We believe that our claim of neutralization to [+NASAL] for vowels in /VVN/  $\rightarrow$  [ $\tilde{V}\tilde{V}$ N] and their statistical equivalence with / $\tilde{V}\tilde{V}$ / vowels is sufficiently credible to be taken as fact for the purposes of our analysis.<sup>19</sup>

## 7.4 By-speaker harmony patterns from Experiment 2

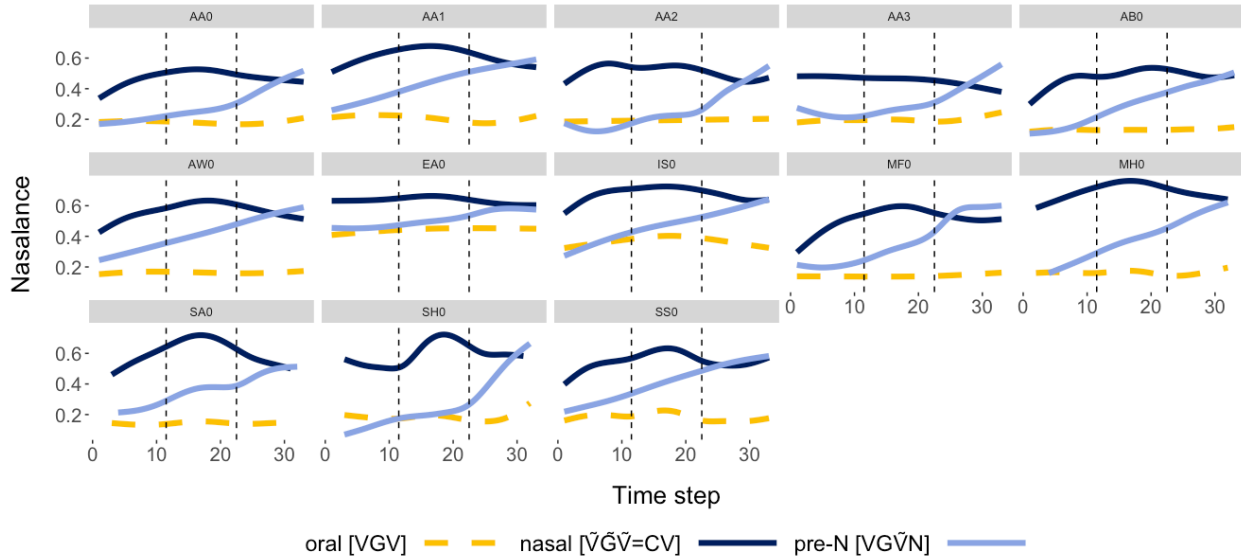


Figure A4: GAM curves for the oral [VG̃V], contrastive nasal [VG̃Ṽ=CV], and pre-N [VG̃VN] conditions, separated by speaker. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VG̃V] sequence for the thirteen speakers that exhibit categorical nasality on /VVN/ vowels.

<sup>19</sup>To be sure, we do not claim that / $\tilde{V}\tilde{V}$ / and /VVN/ are phonetically indistinguishable—they clearly *are* distinguishable, since /VVN/ has a nasal coda, and / $\tilde{V}\tilde{V}$ / does not. We are simply claiming that the phonetic evidence indicates that both / $\tilde{V}\tilde{V}$ / and /VVN/  $\rightarrow$  [ $\tilde{V}\tilde{V}$ N] are phonologically specified as [+NASAL] vowels and any phonetic divergence between the two vowels can be attributed to within-category random variation.

## 7.5 Nasalization in Lahori Panjabi

In section 4.2 we noted that two speakers in Experiment 2 produced /VVN/ vowels with anticipatory nasal coarticulation rather than categorical nasality. GAM curves across [VG̃V] sequences are displayed in Figure A5 for these two speakers. As can be seen by the curves, nasalance across the penultimate pre-glide stem vowel and glide for the pre-N [VG̃VN] condition is proportionally similar to the oral [VG̃V] condition, but a cline-like increase in nasalance begins near the onset of the /VVN/ vowel, only nearing the nasalance level of the [ṼG̃Ṽ=CV] condition at the offset of the [VG̃V] sequence. This pattern suggests that the /VVN/ vowel is not intentionally targeted as [+NAS] by these speakers, which is quite distinct from all other speakers in either Experiment 1 or Experiment 2. Crucially, however, the two speakers that exhibited this pattern grew up in Lahore, a large city of about 11 million people located on the eastern border of Pakistan, and no other speakers in either experiment grew up in this region. While further research is needed, we speculate that the dialect of Panjabi in Lahore displays a distinct pattern of nasality on /VVN/ vowels, such that they do not surface as [+NAS] vowels but instead are coarticulatorily nasalized as a result of the following nasal consonant. We leave it to future research to explore the veracity of the assumption that Lahori Panjabi does indeed represent a distinct dialect in terms of its nasality processes.

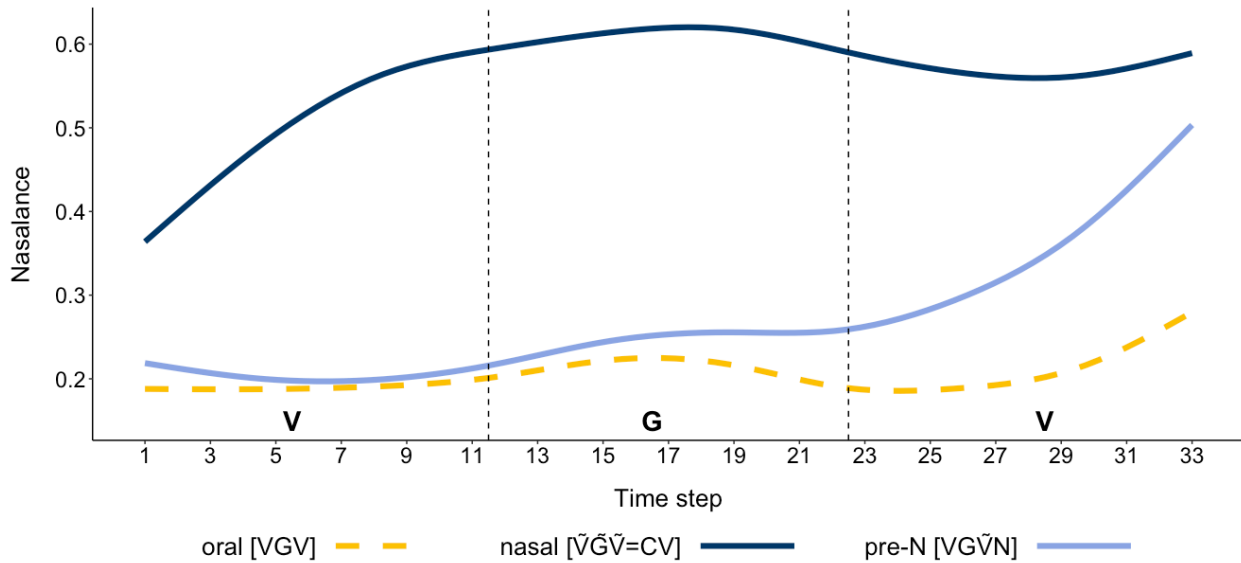


Figure A5: GAM curves for the oral [VG̃V], contrastive nasal [ṼG̃Ṽ=CV], and pre-N [VG̃VN] conditions. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VG̃V] sequence for the two speakers that exhibit coarticulatory nasality on pre-N /VVN/ vowels.