Covert URs: evidence from nasalization in Western Panjabi

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Abstract

Western Panjabi is an Indo-Aryan language spoken primarily in the Punjab province of Pakistan. Long vowels contrast in nasality in the language, but this contrast is neutralized before nasal consonants: [ṼṼN], *[VVN]. This paper presents air pressure data showing that predictably nasal vowels before nasal consonants in Panjabi, [ṼṼN], are phonetically identical to contrastive nasal vowels, /ṼṼ/ (Exp. 1). However, predictable [ṼṼN] and contrastive /ṼṼ/ vowels behave differently in their interaction with a nasal harmony process, in that only contrastive /ṼṼ/ 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 unchanged in any allomorph. 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 & Halle (1968), research in generative phonology has traditionally assumed at least two distinct levels of representation for words and other lexical items. *Underlying representations* (URs) are the abstract forms 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 simply be memorized. Chomsky & 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 & Smolensky 1993/2004: Ch. 9). The UR for an English word like 'price' [ˈpʰɹ̥aɪ̆s] would thus be /pɹaɪs/, a sparse, redundancy-free, minimal specification of only those unpredictable aspects of the phonology and phonetics of 'price' which must be memorized.

Surface representations (SRs), on the other hand, are the forms of morphemes and words that emerge after URs are filtered through a grammar that applies predictable, language-specific, and context-specific phonological processes. The grammar, which is composed of rules or other formal devices, is thus responsible for transforming minimally-specified lexical representations like /pɹaɪs/ ‘price’ to SRs like [ˈpʰɹ̥aĭs], which are full of predictable, redundant, contextually-determined phonetic detail.

In contrast to the sparse, redundancy-free, and phonetically abstract underlying representations encountered in generative phonology, a broad body of experimental literature has argued that lexical representations do, in fact, include phonetically-detailed, predictable, and context-dependent information about the pronunciation of words and morphemes (e.g. Johnson 1997, Bybee 2001, Pierrehumbert 2001, Johnson 2006, Pierrehumbert 2016, Goldrick & Cole 2023, 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 memories of past experiences hearing each word, including detail about speaker identity.

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 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 very 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. Pierrehumbert (2016), Goldrick & Cole (2023) and research cited there. 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 incompatible with abstract representations (e.g. Goldinger 1998, Goldrick & 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 modeling spoken word recognition and phonological priming effects (e.g. Lahiri & Marslen-Wilson 1991, Gaskell & Marslen-Wilson 1996, LoCasto & Connine 2002, Jongman 2004, Lahiri & Reetz 2010, Cornell et al. 2011, Lahiri 2012, Ernestus 2014, Farris-Trimble & Tessier 2019, White et al. 2024), and for understanding phonological aphasias (e.g. Goldrick & Rapp 2007, Buchwald & Miozzo 2011), 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. Kenstowicz & Kisseberth 1979, McCarthy 2007, Hyman 2018). 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 & Kisseberth 1979). More specifically, classical generative phonology holds the rather strong position that an underlying representation can be *completely covert*, with 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 [ʔeːw̥-a] 'is deep' ∼ [ʔeːw̥**i**-tkʰ] 'deep'. O'Hara argues that these alternations cannot be analyzed as the deletion or insertion of [i]. Instead, he proposes that stems like [ʔeːw̥(i)-] contain an underlying final /e/, e.g. /ʔeːw̥e/. Stem-final /e/ deletes outside of initial syllables, but instead raises to [i] when deletion would produce an illicit consonant cluster. As a consequence, the underlying forms of stems like /ʔeːw̥e/ are *covert*: they contain a segment, /e/, which never appears in any surface allomorph (echoing a long line of analyses of 'yer' vowels in Slavic languages, e.g. Gouskova 2012).[1] Analyses making use of covert URs involve a high level of abstraction: speakers must somehow arrive at a stored lexical entry for a stem like /ʔeːw̥e/ 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 & 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 /ʔeːw̥e/ → [ʔeːw̥(i)-]. To the extent that covert underlying representations like /ʔeːw̥e/ can be justified, they motivate richer, more articulated mechanisms for arriving at URs than can be produced by pooling over surface forms.

This paper provides phonetic and phonological evidence from Pakistani Panjabi which highlights the benefits of abstraction in lexical representation. We measure oro-nasal air pressure across three different types of vowels in Panjabi: oral vowels /VV/, contrastive nasal vowels /ṼṼ/, and vowels occurring before a tautomorphemic nasal consonant /VVN/. The results indicate that Panjabi speakers consistently produce /VVN/ vowels with nasalization identical to /ṼṼ/ vowels. However, nasal vowels in /VVN/ interact opaquely with a pattern of nasal harmony triggered by contrastive /ṼṼ/. 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. 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 & Kisseberth 1979, McCarthy 2007) — can be subsumed by surface-oriented general-

[1] The URs we describe as 'covert' have typically been called 'abstract' (e.g. Kenstowicz & Kisseberth 1979, Albright 2002, Krämer 2012, O'Hara 2017, Hyman 2018, Wang & Hayes 2025). We opt for the term 'covert' here to specify more precisely exactly what type of abstract UR we are concerned with: namely, URs which contain segments that never surface faithfully, in any context.

izations, including surface-to-surface relationships between allomorphs of the same morpheme (e.g. Burzio 1996, Scobbie et al. 1996, Hayes 1999, Albright 2002, Cole & Hualde 2011, Allen & Becker 2015, and various others). The pattern of opacity we discuss here cannot be straightforwardly modeled through the use of surface correspondence, because the key forms (derived /VVN/ → [ṼṼN]) 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, McCarthy 2005a, Mascaró 2016). To the extent that surface-oriented approaches *can* account for this data, they do so by implementing a formal distinction between predictable vs. unpredictable phonetic detail, thus recapitulating a core function of abstract URs (e.g. Cole & 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.

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 native Panjabi speakers (33 million) (Bashir & Conners 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 the Pakistani varieties have been published in recent years. 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, but Bashir & Conners (2019: p.45) note that this contrast is confined to the morpheme-final syllable, as shown in (1).

(1) Contrastive vowel nasality in Panjabi

a.	[tɑɑ]	'warmth, fever'	vs.	[tɑ̃ɑ̃]	'that; so that'
b.	[pɑɑʋee]	'cot leg'	vs.	[tʃɑɑʋẽẽ]	'pumicestone'

Crucially, a coda nasal consonant neutralizes the nasality contrast such that no minimal pairs of the shape /CVVN/-/CṼṼN/ exist. This neutralization is likely due to the fact that all /V(V)N/ vowels are said to be characterized by a high degree of nasality (hence [tɑ̃ɑ̃n] 'melody' is a word, but not hypothetical *[tɑɑn]). This description is supported by the results of Zahid & Hussain (2012), who conducted an acoustic study of vowel nasality in 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 & Hussain did not find a difference in nasality between contrastive /ṼṼ/

vowels and /VVN/ vowels in terms of their A1-P0 and A1-P1 values, measurements reported to correlate highly with nasality (Chen 1997, Styler 2017).

		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	ɛ̃ɛ̃	ə				ɔɔ	ɔ̃ɔ̃
Low	tense									
	lax								ɑɑ	ɑ̃ɑ̃

Figure 1: The Panjabi vowel inventory (Shackle 2003)

In addition to the nasality contrast on long vowels 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 through all glides (/j/ and /ʋ/) and vowels until a non-glide consonant blocks the spread. For example, words with the shape found in (2a-b), in which the word-final vowel is underlyingly /ṼṼ/, are realized with nasality across the [VVGVV] sequence (Bhatia 1993, Bashir & Conners 2019). However, these descriptions of the nasal harmony process do not clarify whether the [ṼṼN] vowel in (2c-d) also instigates the spread of nasality, which serves as the central question of the second experiment discussed in the present work (section 4).[2]

(2) Nasal harmony in Panjabi

a.	/sɑɑ-ʋɑ̃ɑ̃/	→	[sɑ̃ɑ̃ʋ̃ɑ̃ɑ̃]	'breath-PL'
b.	/mɑtʃii-jɑ̃ɑ̃/	→	[mɑtʃĩĩj̃ɑ̃ɑ̃]	'fish-PL'
c.	/ɑɑʋɑɑm/	→	?[ɑ̃ɑ̃ʋ̃ɑ̃ɑ̃m]/[ɑɑʋɑ̃ɑ̃m]	'general public'
d.	/siijɑɑɳ/	→	?[sĩĩj̃ɑ̃ɑ̃ɳ]/[siijɑ̃ɑ̃ɳ]	'recognition'

There are two possibilities with regard to the participation of [ṼṼN] vowels in nasal harmony. First, and perhaps most straightforwardly, if [ṼṼN] vowels are indeed phonetically identical to /ṼṼ/ vowels in Panjabi, it would be logical to assume that both vowel types instigate the nasal harmony process in a similar fashion. After all, no nasality difference exists on the surface that distinguishes the two vowels.

On the other hand, it is possible that, despite being phonetically identical to contrastive /ṼṼ/ vowels, non-alternating [ṼṼN] 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 [ṼṼN] 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 /ṼṼ/ and underlyingly oral /VVN/ → [ṼṼN]

[2] /ɑɑʋɑɑm/ is historically complex (/ɑɑʋ-ɑɑm/ 'PL-common man') but may not be synchronically analyzable. In any case, [ɑ̃ɑ̃m] is non-alternating under either morphological analysis, which is the relevant point here.

can be leveraged to explain the uneven application of harmony: only underlying, contrastive nasal /ṼṼ/ is a harmony trigger. Without positing a difference in the underlying representations of contrastive /ṼṼ/ vowels and non-alternating [ṼṼN] nasal vowels in (2), it is difficult to explain why the two vowel types behave differently in their interaction with leftward nasal spread.

Crucially, [ṼṼN] vowels in words like those in (2c-d) 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 [ṼṼN] vowels are underlyingly distinct from contrastive /ṼṼ/ vowels (i.e. there are no alternations like /ɑɑʋɑɑ=m/ → [ɑɑʋɑ̃ɑ̃=m] vs. /[ɑɑʋɑɑ=C] for these forms). As a result, the only direct, observed information speakers have regarding the nasality of pre-nasal [ṼṼN] vowels in words like 'citizens' and 'recognition' (2c-d) is that they are consistently realized as [+NAS]. Given that speakers do not have any direct surface evidence that [ṼṼN] vowels are underlyingly oral, surface-oriented models like exemplar theory lack the necessary mechanisms to distinguish predictable pre-nasal vowels in [ṼṼN] from underlying contrastive nasal vowels /ṼṼ/.

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

Experiment 1 measured the phonetic realization of Panjabi non-alternating [ṼṼN] vowels and compared their realization to contrastive /ṼṼ/ and oral /VV/ vowels in the language. As mentioned above, Zahid & Hussain (2012) analyzed [ṼṼN] vowels for three Panjabi speakers and did not discover a difference between their realization and the realization of contrastive /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 acoustic measurements.

3.1 Participants

Twenty native Panjabi speakers participated in the study (eleven men and nine women) ranging in age from 22-79 (μ = 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 distance 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/ (CṼṼ), and pre-nasal [ṼṼN] (CVVN). The complete list of tokens is given in Figure A1 of the appendix. 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 CṼṼ condition had contrastive /ṼṼ/ 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 excluded from this condition to avoid the effects of carryover coarticulation. Whereas the oral CVV and /ṼṼ/ CṼṼ conditions provide clear baselines of orality and nasality, the CVVN condition allows for a comparison between the realization of [ṼṼN] 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 (Henderson 1984, Bell-Berti 1993, Delvaux et al. 2008). To control for this, a balanced range of vowel qualities was included in each condition as well.

3.3 Procedure

All participants were recorded individually in a sound-attenuated room at a university in Rawalpindi, Pakistan. A native Panjabi research consultant provided participants with a consent form in Panjabi Shahmukhi script 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 was used to measure air pressure from the nose and mouth separately at a sampling rate of 11,025 kHz. The mask was 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 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 67 monosyllabic tokens in a randomized order using a Python Graphical User Interface. Participants read each item into the mask four times: twice slowly and twice using fast/rapid speech. The experiment included speech rate as a condition to test whether vowel duration modulates the degree of nasality on /VVN/ vowels (Solé 1992, 1995). 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

Recordings were hand-annotated with segment boundaries using Praat (Boersma & Weenink 2015). Details of the annotation procedure are outlined in the Appendix.

After annotation, a Praat script iterated through the annotated files, converting the oral and nasal air pressure channels to intensity tracks. A series of R scripts extracted mean nasalance values ($A^n/A^n + A^o$) over 11 time-normalized windows for each segment from these intensity tracks. The values were then saved in a data frame for subsequent analysis.

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 CṼṼ 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 difference was found between tokens uttered in slow speech and tokens uttered in fast speech, so all four repetitions of each token were lumped together in the model. This fact is evident from comparing the two low-pass filtered nasalance traces in Figure 2 for the word /biin/. 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 significant durational difference, nasalization is categorically implemented across the entire span of both CVVN vowels. This indicates that nasality on the CVVN vowel is intentionally implemented and controlled by the speaker rather than resulting from a coarticulatory effect due to the vowel's adjacency to the nasal consonant (Solé 1992, 1995).

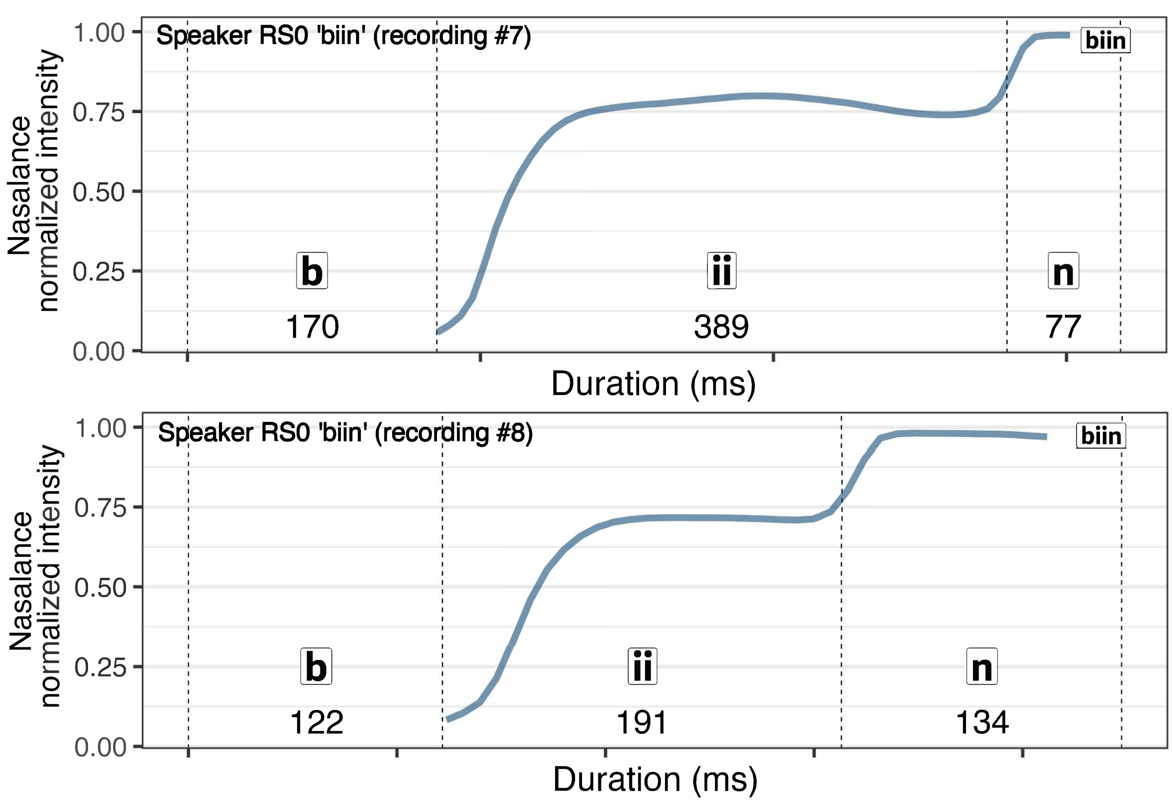

Figure 2: Nasalance traces of the word /biin/ uttered by the same speaker in quick succession that differ only in the speech rate. The traces show the normalized nasalance amplitude across the length of the word.

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. 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).

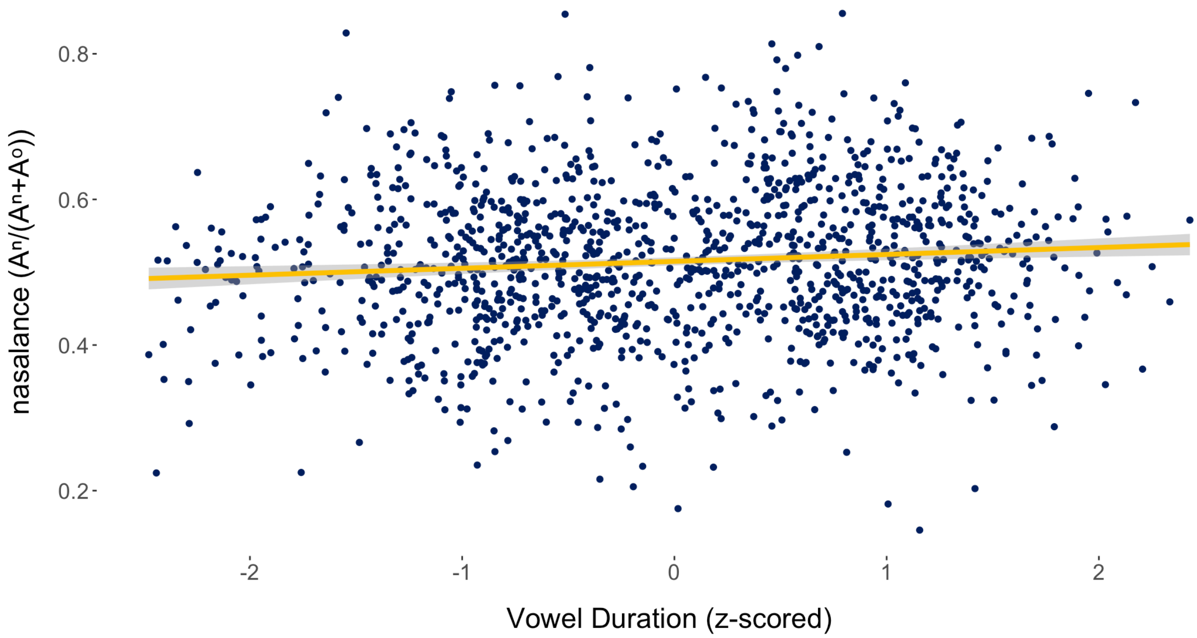

Figure 3: Scatterplot showing the .09 Pearson Correlation value between speech rate and mean nasalance for all CVVN vowels produced by nineteen speakers in experiment 1.

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 40% across the length of the oral vowel. For the contrastive /ṼṼ/ vowel condition (CṼṼ), 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 [ṼṼN] vowels in the CVVN condition, they follow a very similar pattern to contrastive /ṼṼ/ vowels, 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.

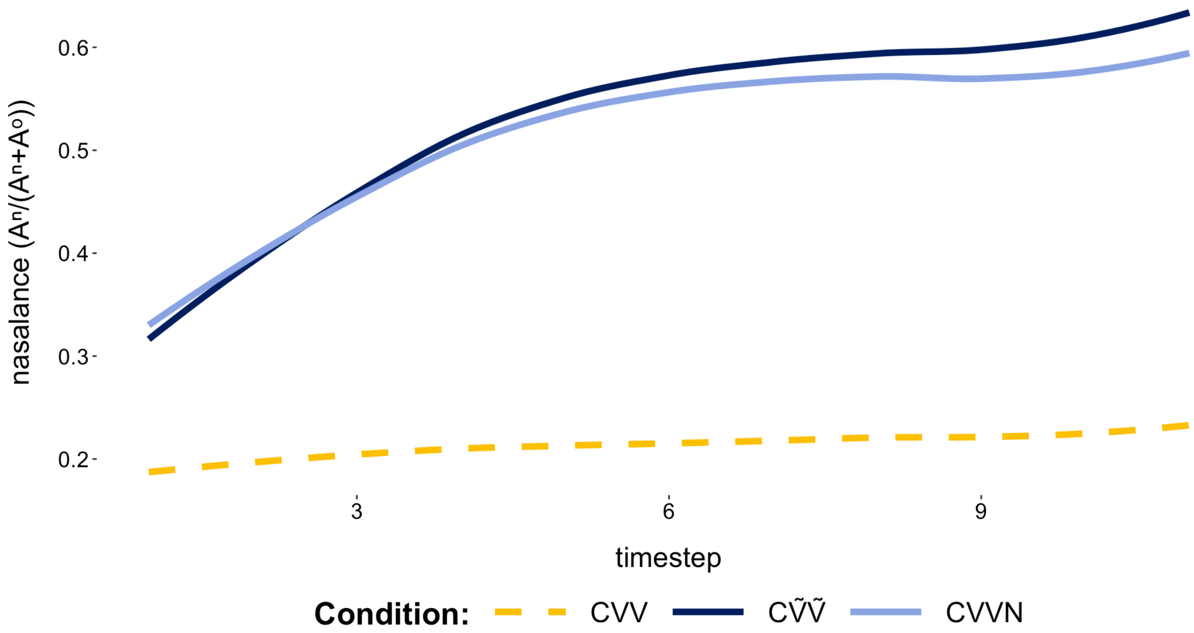

Figure 4: GAM curves separated by condition showing mean vowel nasalance across 11 normalized timesteps for all monosyllabic tokens from experiment 1 for nineteen speakers.

To quantitatively compare the nasalance between CṼṼ 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 (CṼṼ 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 CṼṼ 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 in the first 1/3 of the vowel, steps 5-8 recoded in the second 1/3, and steps 9-11 recoded in 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. A random intercept was included for word. By-speaker random slopes and intercepts were included for CONDITION.

The main effects of CONDITION, TIMESTEP, and VOWELQUALITY were effect coded, so the intercept (β_0) refers to the grand mean of nasalance averaged over all levels of the main effects, and the remaining coefficients — β_1 - β_{14} in table 1 — equal the difference between the grand mean and the listed factor level, controlling for the other predictors. The results of the LMER model are provided in table 1.

The CONDITION*TIMESTEP interaction was significant at the beginning and end of the vowel, which means that the degree of nasalance difference between CVVN and CṼṼ is not consistent across these timesteps. Nevertheless, the effect sizes of these interactions can be considered inconsequential since neither interaction deviates from the overall main effect by more than .008 (0.8%) in nasalance. Thus, it is safe to examine the main effect of CONDITION without worrying about interaction effects clouding its interpretability.

Similarly, the main effect of 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. However, because the effect sizes across vowel qualities were relatively minimal and vowel quality was balanced across the different nasality conditions, it is safe to set these effects aside as well.

Disregarding the small interaction and vowel quality effects, the primary takeaway from the model for our purposes is located in the first three rows. Specifically, neither level of the main effect of CONDITION (CṼṼ and CVVN) reach significance. That is, the null hypothesis that mean nasalance is identical for CṼṼ and CVVN vowels across their entire span cannot be rejected.

Predictor	β	95% CI	*t*	*p*
Intercept (grand μ)	.533	[.505, .561]	37.47	< .001 ***
CVVN	-.008	[-.02, .004]	-1.36	.18
CṼṼ	.008	[-.004, .02]	1.36	.18
Beg	-.106	[-.108, -.104]	-115.59	< .001 ***
Mid	.040	[.038, .041]	43.15	< .001 ***
Fin	.067	[.064, .069]	63.05	< .001 ***
uu	.038	[.016, .059]	3.44	.002 **
ii	.052	[.021, .082]	3.34	.002 **
oo	-.046	[-.071, -.022]	-3.66	< .001 ***
ɔɔ	-.009	[-.04, .021]	-.60	.55
ee	-.012	[-.061, .037]	-.47	.64
ɑɑ	-.022	[-.04, -.004]	-2.44	.02 *
CVVN:Beg	.009	[.007, .01]	9.23	< .001 ***
CVVN:Mid	-.0008	[-.003, .001]	-0.87	0.38
CVVN:Fin	-.008	[-.01, -.006]	-7.27	< .001 ***

Table 1: LMER model summarizing the effect of CONDITION (CṼṼ, CVVN), TIMESTEP (beginning, middle, final), the CONDITION*TIMESTEP interaction, and VOWELQUALITY (ɑɑ, ɔɔ, oo, ee, uu, ii) on mean nasalance for nineteen speakers: lmer(nasalance~CONDITION*TIMESTEP + VOWELQUALITY + (1 + CONDITION|speaker) + (1|word)

To directly compare whether or not CṼṼ and CVVN vowels are significantly different from each other in terms of nasalance, we extracted pairwise comparisons between the two vowel conditions from the lmer model in Table 1 using the *emmeans()* function in R (Lenth 2024). Under this method, the nasalance of the two vowel conditions are compared, averaging over other predictors in the model.

Predictions of the pairwise comparison are provided in Table 2 and show that no significant difference in nasalance was found between CVVN and CṼṼ vowels. This means that the null hypothesis that the two vowels are indistinguishable in terms of their nasalance values cannot be ruled out.

Comparison	β	95% CI	*t*	*p*
CṼṼ - CVVN	.016	[-.007, .039]	1.36	.17

Table 2: Pairwise comparison showing the effect of vowel condition (CVVN vs. CṼṼ) on mean nasalance. Results were extraced using emmeans(), which averages over other predictors in the model: emmeans(nasalance~CONDITION + (1 + CONDITION|speaker) + (1|word).

Importantly, while no effect of CONDITION was found to alter the mean nasalance of these two vowels, the results do not allow us to conclude that the nasalance of CṼṼ and CVVN vowels are equivalent. Rather, 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 identical. 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 (Wellek 2010, Lakens et al. 2018, Bonett 2021). If the confidence interval for the difference is wholly contained within that interval, the hypothesis that a 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 CṼṼ and CVVN conditions.

To determine a region of practical equivalence (*RoPE*) for mean nasalance in Panjabi, we first grouped CṼṼ 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. Finally, the *RoPE* was defined as ± 2 standard deviations of nasalance for the speaker with the narrowest variation. Because all vowels in the CṼṼ condition in this experiment are phonologically contrastive nasal vowels, any variation in nasalance on these vowels within an individual speaker can be treated as negligible. Setting the *RoPE* to capture 95% of tokens (±2SDs) produced by the speaker with the strictest distribution in nasalance therefore establishes a conservative threshold below which variation can be interpreted as within-category random phonetic noise, rather than a cross-category intentional phonological difference. Using this method, we estimate the *RoPE* for nasalance on CṼṼ vowels in Panjabi to be ±.061.

Figure 5 shows the proposed *RoPE* along with the nasalance data from vowels in the CṼṼ condition from all speakers in experiment 1. The yellow points on the plot represent the mean nasalance for CṼṼ vowels for each speaker from experiment 1, with the tails indicating ± 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 CṼṼ vowel can reliably be interpreted as nasal. The magnitude of the suggested *RoPE* of ±.061 shown in blue can be interpreted in a similar way.

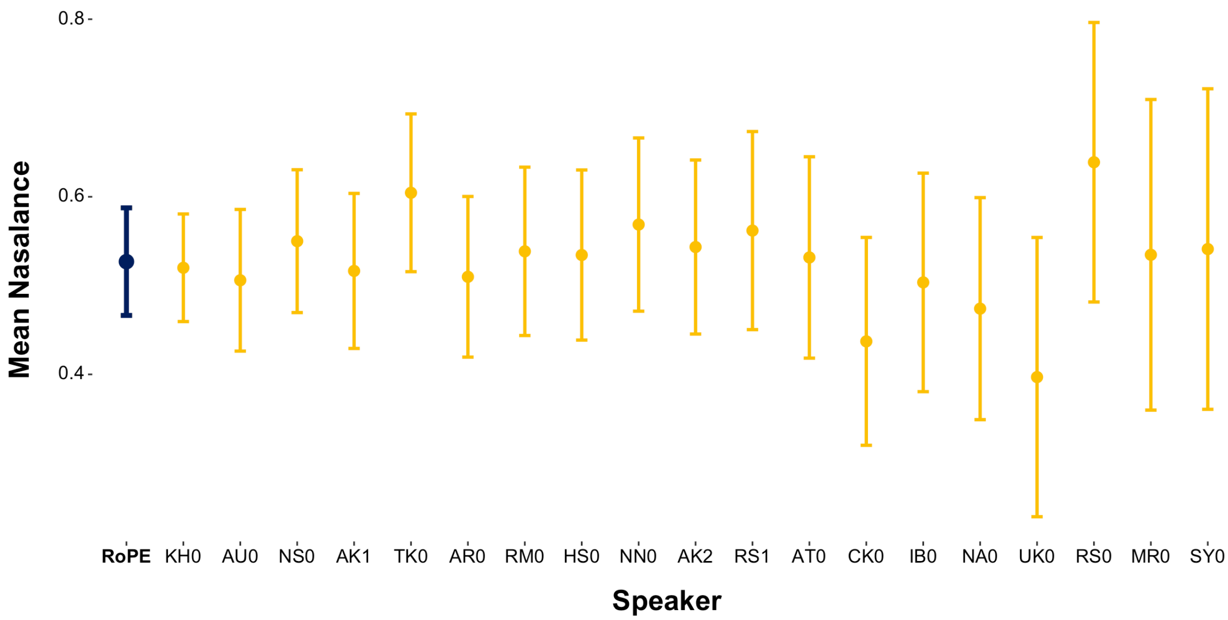

Figure 5: Dot and whisker plot showing mean nasalance of CṼṼ vowels from experiment 1. The yellow dots and tails represent the mean CṼṼ vowel nasalance for each speaker and ± two standard deviations around this mean nasalance value respectively. Speakers are ordered from left to right by magnitude of standard deviation. The blue point shows the mean nasalance across all speakers, and its tails represent the proposed *RoPE* of ±.061.

Reexamining the 95% CI of the pairwise comparison of nasalance extracted using emmeans() between CVVN and CṼṼ in table 2, which compares nasalance in CVVN vowels to nasalance in CṼṼ vowels, we see that the entire confidence interval ([-.007, .039]) falls within the bounds of the proposed *RoPE* (±.061). Therefore, it seems appropriate to conclude that the mean nasalance of the two vowel types is both statistically and practically equivalent. This allows us to assert that CVVN vowels surface as phonologically [+NAS] in the same way as CṼṼ vowels in Panjabi.

To sum up, the results of experiment 1 confirm and extend the findings from the acoustic analysis in Zahid & Hussain (2012): [ṼṼN] vowels are not meaningfully different from /ṼṼ/ vowels with respect to their phonetic nasality.[3]

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

Experiment 1 found that contrastive /ṼṼ/ and non-alternating [ṼṼN] 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 another phonological process in Panjabi: leftward nasal spread. Specifically, experiment 2 is designed to test if differences exist between contrastive /ṼṼ/ and non-alternating [ṼṼN] with respect to their ability to trigger nasal harmony in Panjabi.

[3]The discussion here assumes that – because they are produced with identical nasality – /ṼṼ/ and [ṼṼN] are *perceptually* identical as well. Nevertheless, the production studies in this paper cannot answer questions about perception, so future research is needed to determine whether or not contrastive /ṼṼ/ vowels are perceptually distinct from [ṼṼN] vowels to listeners. See also Beddor & Krakow (1999).

The results of experiment 1 help frame two potential hypotheses regarding the interaction of surface [ṼṼN] vowels with nasal harmony. The first hypothesis asserts that, because contrastive /ṼṼ/ and non-alternating [ṼṼN] vowels appear to be identical 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 [ṼṼN] is predictable rather than contrastive in Panjabi. As such, surface [ṼṼN] 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 /ṼṼ/ — which would be underlyingly nasal — and underlyingly oral vowels in /VVN/.

Thus, a second hypothesis is that /ṼṼ/ and [ṼṼN] 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 /ṼṼ/ triggers harmony, while underlying oral /VVN/ → [ṼṼN] does not.

Importantly, contextually nasal vowels /VVN/ → [ṼṼN] may be non-alternating. There is thus no surface evidence that these vowels are anything other than nasal. For this reason, hypothesis 2 is only stateable 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 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 (μ = 28.2; median = 27). Similar to the first experiment, stimuli were sourced from three main vowel types: oral /VV/, contrastive nasal /ṼṼ/, and non-alternating pre-nasal [ṼṼN] 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 (VVGVV) 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 a CV postposition beginning with an oral stop (e.g. /ɑɑʋɑɑm=də/ 'general public=GEN'). In addition to these three conditions, words ending in a contrastive /ṼṼ/ vowel followed by a nasal-initial NV postposition were included as an additional condition. Bashir & Conners (2019) 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 /ṼṼ/ vowels are immediately followed by a postposition beginning with a nasal consonant, the contextual environment of /ṼṼ/ more closely mimics that of [ṼṼN] 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. Twenty-seven filler items were also randomly dispersed throughout the token set. Complete glosses of all tokens included in the experiment are provided in Figure A2 in the Appendix.

oral /VV/		pre-nasal [ṼṼN]	
/sət-ɑɑjii də/	‘27’	/dʒəʋɑɑɳ də/	‘a youth’
/ɔɔlii-jɑɑ də/	‘pious men’	/ədʒəʋɛɛɳ də/	‘omum seed’
/həʋɑɑ də/	‘air’	/siijɑɑɳ də/	‘recognition’
/tʃoo-ʋii də/	‘24’	/teejɑɑɳ də/	‘attention’
/pɑɑʋee də/	‘cot leg’	/lɛɛ-jɑɑɳ de/	‘taking’
/beeʋɑɑ də/	‘widow’	/ɑɑʋɑɑm də/	‘general public’
/dəʋɑɑ də/	‘medicine’		
/tɑɑʋuu də/	‘uncle’		
/ʋəkʰɑɑʋee də/	‘boasting’		
/mʊkʰiijɑɑ də/	‘chief’		

contrastive nasal /ṼṼ=NV/		contrastive nasal //ṼṼ=CV/	
/tʃɑɑʋẽẽ nʊ/	‘pumicestone’	/tʃɑɑʋẽẽ də/	‘pumicestone’
/uu-ʋẽẽ nʊ/	‘in that way’	/uu-ʋẽẽ də/	‘in that way’
/doo-ʋɑ̃ɑ̃ nʊ/	‘both sides’	/doo-ʋɑ̃ɑ̃ pɑɑse/	‘both sides’
/kii-ʋẽẽ nʊ/	‘somehow’	/kii-ʋẽẽ də/	‘somehow’
/ɛɛ-ʋẽẽ nʊ/	‘in vain’	/ɛɛ-ʋẽẽ də/	‘in vain’
/matʃii-jɑ̃ɑ̃ nɪ/	‘fish-PL’	/matʃii-jɑ̃ɑ̃ də/	‘fish-PL’
/tiiʋĩĩ nɪ/	‘woman’	/tiiʋĩĩ də/	‘woman’
/sɑɑ-ʋɑ̃ɑ̃ nɪ/	‘breaths’	/sɑɑ-ʋɑ̃ɑ̃ də/	‘breaths’

Table 3: Experiment 2 tokens.

Both the contrastive oral /VV/ and contrastive nasal /ṼṼ/ conditions provide established baselines for an oral vowel with no nasality in the signal and a /ṼṼ/ vowel that triggers nasal harmony, respectively. The [ṼṼN] vowel condition, on the other hand, serves as the focus of the experiment. Importantly, VVN sequences from the [ṼṼN] 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 phonetically identical to contrastive /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-nasal vowels in [ṼṼN] trigger nasal harmony to the same extent as contrastive /ṼṼ/. Section 4.2.1 discusses the apparent optionality of nasal harmony triggered by contrastive /ṼṼ/. Section 4.2.2 analyzes tokens with harmony triggered by contrastive /ṼṼ/. Section 4.2.4 shows that pre-nasal [ṼṼN] vowels do not trigger nasal harmony, despite being as strongly nasalized as contrastive /ṼṼ/ vowels (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 /VV/ and contrastive nasal /ṼṼ/ 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 /VV/ and the contrastive /ṼṼ=CV/ and /ṼṼ=NV/ conditions uniformly, but productions of the pre-nasal [ṼṼN] condition fell into two distinct patterns that require individual attention. All fifteen speakers lacked nasal harmony across the preceding VVG sequence in the [ṼṼN] condition (section 4.2.4). Thirteen speakers categorically nasalized the [ṼṼN] vowel immediately preceding the nasal consonant (section 4.2.3). However, the remaining two speakers systematically lacked categorical nasality on all [ṼṼN] vowels, instead demonstrating a pattern of anticipatory coarticulation. We discuss these two speakers in the Appendix, where we speculate that their productions arise from dialectical differences; 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 /ṼṼ=CV/ and /ṼṼ=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 44% of contrastive /ṼṼ/ tokens (n=399), nasal harmony was not triggered by /ṼṼ/. 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-ʋẽẽ də/ 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 [VVGVV] 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.

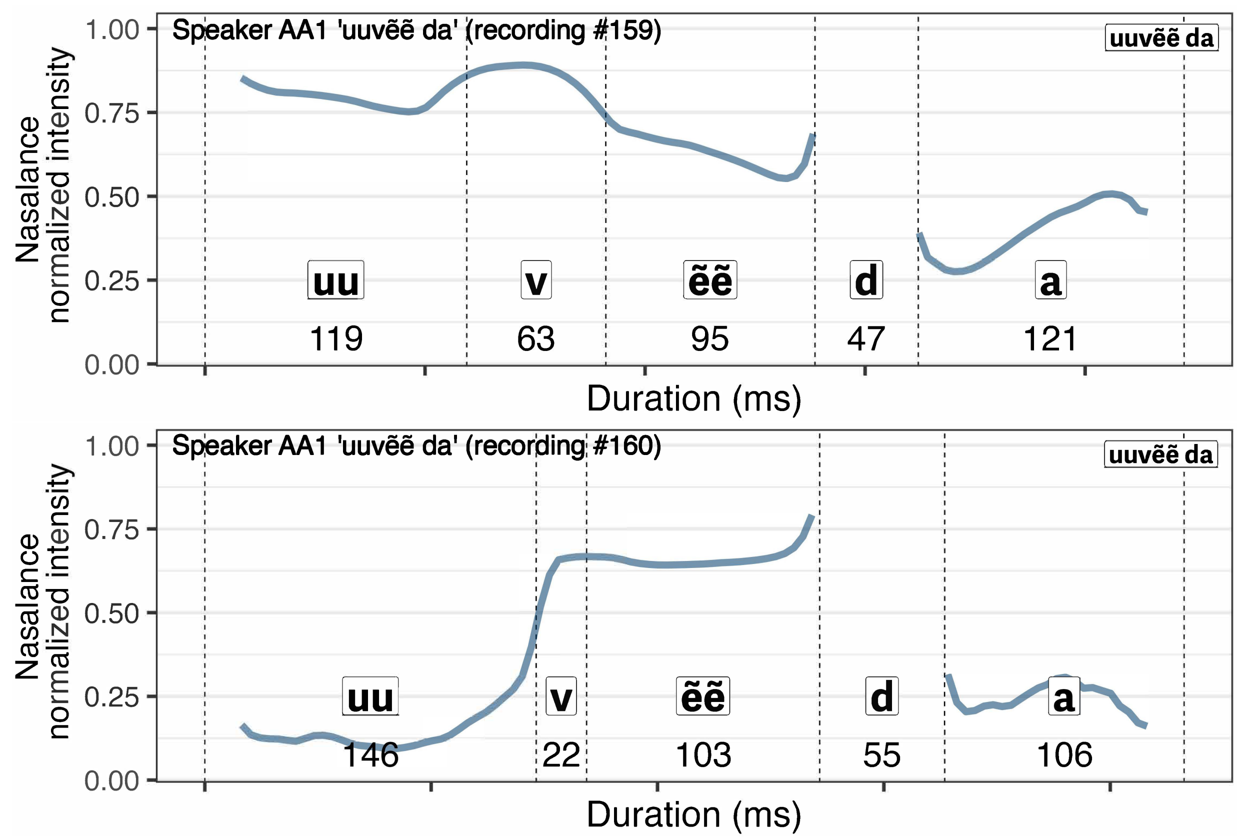

Figure 6: Nasalance traces for two different productions of /uuʋẽẽ/ by the same speaker in quick succession that differ only in the application of nasal harmony. The y-axis corresponds to nasalance, calculated in Praat by taking the normalized proportion of nasal air pressure to the total amount of air 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 /ṼṼ=CV/ and /ṼṼ=NV/ conditions. Moreover, harmony was virtually absent in the [ṼṼN] condition, as we discuss below.[4] 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 /ṼṼ=CV/ and /ṼṼ=NV/ conditions were removed to prevent the obfuscation of the harmony pattern. This was accomplished for each speaker by removing tokens from the /ṼṼ=CV/ and /ṼṼ=NV/ conditions in which the penultimate pre-glide vowel exhibited a mean nasalance clustering with the mean nasalance of penultimate pre-glide vowels in the oral /VV/ condition for that speaker. For example, Figure 7 shows a density plot depicting the concentration of mean nasalance for pre-glide vowels /VVG/ when followed by /ṼṼ=CV/ and /ṼṼ=NV/ for speaker AW0. As is evident, the distribution is bimodal, with the large majority of penult pre-

[4]Across the dataset, a small number of tokens in the [ṼṼN] condition showed unusually high nasalance across the full [VVGṼṼN] sequence. Similarly, a few utterances in the /ṼṼ=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.

glide stem vowels exhibiting a mean nasalance of approximately .51-.53. Conversely, another smaller concentration of penultimate vowels cluster around a mean nasalance of roughly .25. The vertical line shows the approximate cut in which tokens with mean nasalance to the left of the line were removed and tokens with mean nasalance to the right of the line retained. No tokens from the pre-nasal [ṼṼN] condition were removed in this process. Thus, the comparison between contrastive /ṼṼ/ vowels and [ṼṼN] vowels in this study includes only those tokens in the contrastive /ṼṼ=CV/ and /ṼṼ=NV/ conditions in which the nasal harmony process *does* apply. That is, tokens like recording #160 (bottom panel) in figure 6 above were removed.

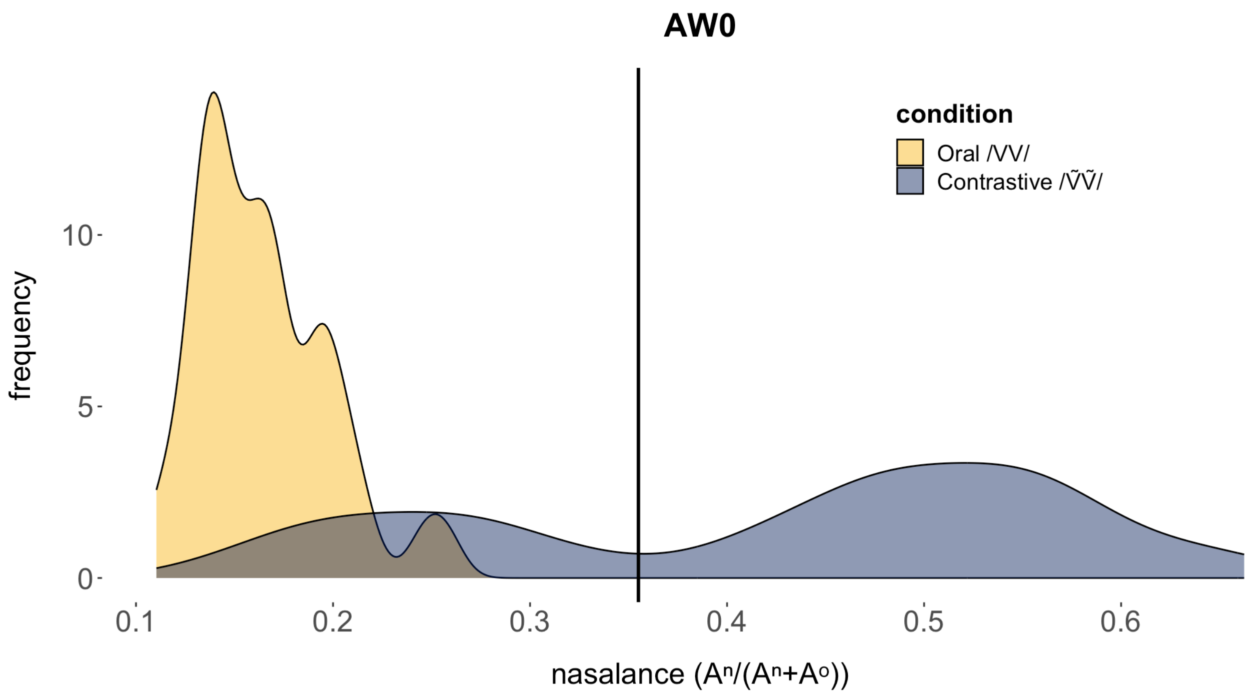

Figure 7: Density plot showing the distribution of mean nasalance for penultimate vowels for speaker AW0. Contrastive /ṼṼ/ includes penultimate vowels from both the /ṼṼ=CV/ and /ṼṼ=NV/ conditions. The plot shows a bimodal distribution for penultimate vowels preceding contrastive /ṼṼ/ (= /VVGṼṼ/), with two distinct peaks around .25 and .52. The vertical line marks the cutoff point for speaker AW0, in which tokens with a mean nasalance to the left of the line were removed from the analysis. The multimodal distribution in the oral condition reflects inherent nasalance differences across vowel qualities (Bell-Berti 1993).

4.2.2 Contrastive /ṼṼ/ and nasal harmony

Figure 8 displays GAM curves fit to nasalance at each of the 33 timesteps across the [VVGVV] sequence for the oral /VV/ and contrastive /ṼṼ=CV/ conditions, for all fifteen speakers.[5] As expected, the oral /VV/ condition exhibits a relatively stable nasalance at about 20% across the entire [VVGVV] sequence. Tokens from the contrastive /ṼṼ=CV/ condition, on the other hand, show

[5]Because nasalance measurements were taken at 11 equidistant timesteps for each segment, figure 8 and other similar figures reporting nasality in [VVGVV] 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 [VV].

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 through the end of the word. This pattern is qualitatively consistent with a process of nasal harmony triggered by the final /ṼṼ/ 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 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 /VV/ and contrastive /ṼṼ=CV/ conditions across the length of the [VVGVV] sequence.

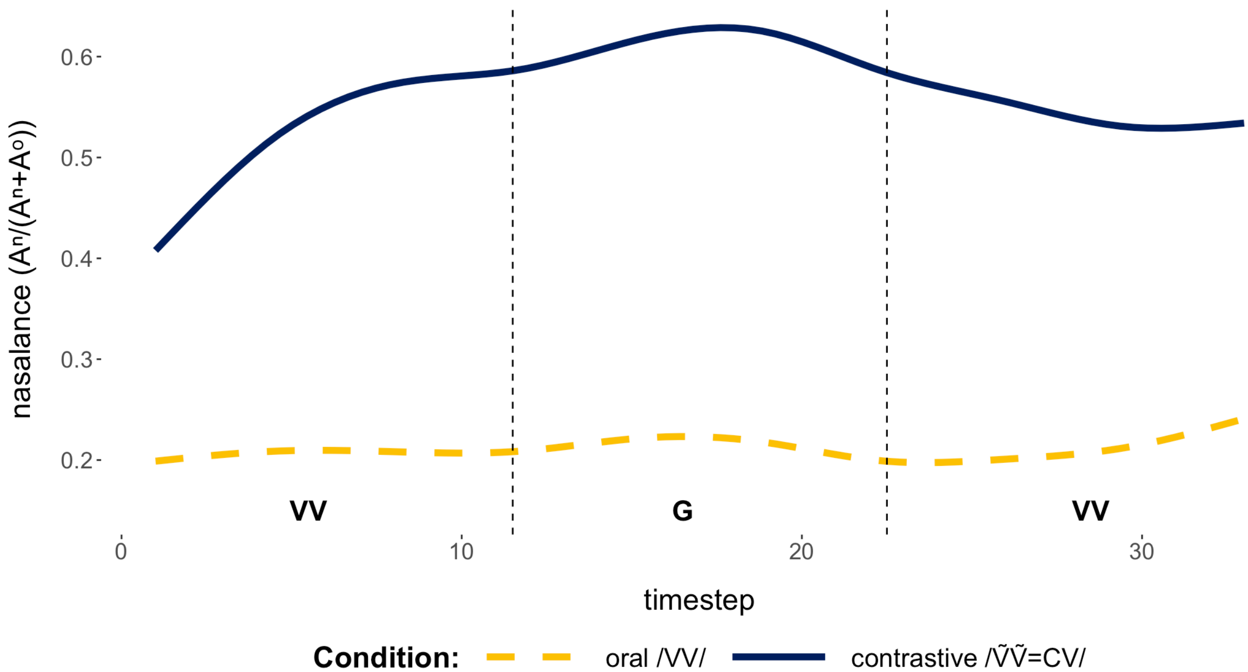

Figure 8: GAM curves for the oral /VV/ and contrastive /ṼṼ=CV/ conditions in experiment 2. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VVGVV] sequence for all 15 speakers in the experiment. Vertical dashed lines represent segment boundaries.

4.2.3 Nasality of [ṼṼN] vowels

The crucial condition in this experiment is pre-nasal [ṼṼN]. The GAM curves in Figure 9 show that nasalance on the penultimate, pre-glide stem vowel does not diverge from the oral /VV/ 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 [ṼṼN] vowel. Strikingly, nasalance on the final vowel itself in the [ṼṼN] condition resembles the level of nasalance found on the final vowel in the contrastive /ṼṼ=CV/ condition through most of its duration.

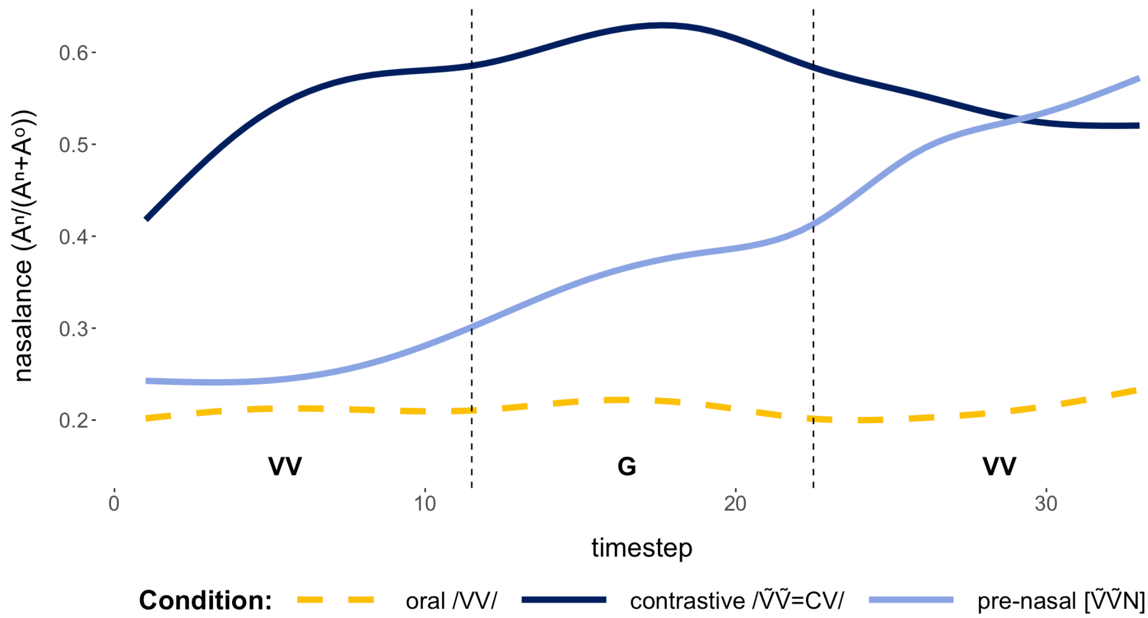

Figure 9: GAM curves for the oral /VV/, contrastive /ṼṼ=CV/, and pre-nasal [ṼṼN] conditions in experiment 2. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VVGVV] sequence for the 13 speakers in the experiment who categorically nasalized the word-final vowel in the pre-nasal [ṼṼN] condition. Vertical dashed lines represent segment boundaries.

To confirm that [ṼṼN] vowels are identical in nasalance to contrastive nasal vowels, we first ran a linear mixed effects model (table 4) comparing nasalance on the final vowel between the /ṼṼ=CV/ and [ṼṼN] conditions. CONDITION (2 levels) was included as a 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, the three levels of the TIMESTEP effect roughly correspond to the first third, middle third, and final third of the final vowel in the [VVGVV] sequence. In addition, including a main effect of VOWELQUALITY (4 levels) did result in a significantly better fit to the data ($\chi^2(3) = 15.17$, $p = .002$ **), so it was retained in the model. By-speaker random slopes and intercepts were included for condition and random intercepts for word. All levels of the main effects – CONDITION, TIMESTEP – are included in the model output displayed in table 4 for clarity.

As is evident from the final three rows in table 4, the interaction between CONDITION and TIMESTEP is significant, with the effect of CONDITION at each level of TIMESTEP diverging significantly in opposite directions. Still, the effect size at each timestep remains relatively small, so the absence of a significant difference between the nasalance of [ṼṼN] and contrastive /ṼṼ=CV/ vowels observed in the first three rows is likely reliable.

Predictor	β	95% CI	*t*	*p*
Intercept (grand μ)	.550	[.506, .595]	24.2	< .001 ***
ṼṼN	-.004	[-.034, .027]	-.24	.82
Contrast. /ṼṼ=CV/	.004	[-.027, .034]	.24	.82
Beg	-.023	[-.025, -.021]	-19.96	< .001 ***
Mid	.002	[0, .005]	2.07	.04 *
Fin	.021	[.018, .023]	15.85	< .001 ***
ii	.125	[.064, .187]	4.0	.003 **
ee	-.011	[-.056, .034]	-.49	.64
ɛɛ	-.055	[-.121, .01]	-1.65	.13
ɑɑ	-.059	[-.093, -.025]	-3.4	.008 **
ṼṼN:Beg	-.040	[-.043, -.038]	-35.16	< .001 ***
ṼṼN:Mid	.008	[.006, .01]	6.95	< .001 ***
ṼṼN:Fin	.032	[.03, .035]	24.98	< .001 ***

Table 4: Results of the LMER model — lmer(nasalance CONDITION*TIMESTEP + VOWELQUALITY + (1 + CONDITION|speaker) + (1|word) — predicting nasalance across the final vowel for 13 speakers who categorically nasalize pre-nasal [ṼṼN] vowels. Effect-coded fixed effects include CONDITION, TIMESTEP, VOWELQUALITY, and CONDITION*TIMESTEP.

Nevertheless, to compare nasalance values between the two conditions more closely, we extracted pairwise comparisons for each third of the vowel from the lmer model in Table 4. The results are summarized in Table 5. Pairwise comparisons showed no significant difference in nasalance between the two vowel types in the final 2/3 of the vowel. The *RoPE* for contrastive nasal vowels in the /ṼṼ=CV/ condition — calculated in the same way as described above — was established at ±.051. For the middle and final thirds of the vowel, the lower bounds of the 95% CIs extend well beyond -.051, suggesting that [ṼṼN] vowels are potentially *more* nasalized than final /ṼṼ=CV/ vowels. This potential difference is consistent with the influence of following context: [ṼṼN] vowels precede a nasal consonant, which maximizes nasalance, whereas /ṼṼ=CV/ vowels precede an oral stop, which typically exhibits minimal nasalance.

Examining the upper bounds, the difference in the final third of the vowel (+.004) lies well within +.051, supporting the interpretation that [ṼṼN] vowels are at least as nasalized as /ṼṼ=CV/ in this portion of the vowel. In contrast, for the middle third, the upper bound extends beyond the proposed *RoPE* by .001, so statistical equivalence between the two vowels in the middle interval cannot be confirmed.

Comparison	β	95% CI	*t*	*p*
(Beg 1/3) /ṼṼ=CV/ - ṼṼN	.088	[.027, .149]	2.82	.005 **
(Mid 1/3) /ṼṼ=CV/ - ṼṼN	-.009	[-.070, .052]	-.28	.78
(Fin 1/3) /ṼṼ=CV/ - ṼṼN	-.057	[-.119, .004]	-1.84	.07

Table 5: Results of three LMER models predicting nasalance across the final, middle, and beginning positions of the final vowel for 13 speakers who categorically nasalize [ṼṼN] vowels. CONDITION (/ṼṼ=CV/ and [ṼṼN]) was included as a dummy-coded fixed effect.

The results for the first 1/3 of the vowel show a significant difference in nasalance between the two conditions of about 8.8%. As we argue in the next section, this is likely a consequence of the fact that nasal harmony applies in contrastive /VVGṼṼ/ → [ṼṼ.G̃ṼṼ], but not in pre-nasal /VVGVVN/ → [VV.GṼṼN]. If the glide is fully nasalized in [ṼṼ.G̃ṼṼ] but not in [VV.GṼṼN], then we expect to find evidence of an oral-to-nasal transition at the beginning of the final vowel in [VV.GṼṼN]. Taking that effect into account, it seems reasonable to conclude that contrastive /ṼṼ=CV/ vowels and pre-nasal [ṼṼN] vowels are equivalent in terms of their surface nasalance, not only in monosyllabic tokens (experiments 1) but in longer words as well. Apparent differences between them arise from different patterns of local, anticipatory nasal coarticulation with the preceding glide.

To sum up, pre-nasal [ṼṼN] and contrastive /ṼṼ=CV/ vowels do not show a statistically significant difference in nasality for the middle and final thirds of the final vowel. Furthermore, while the beginning third of /ṼṼ=CV/ vowels was significantly more nasalized than the same portion of [ṼṼN] vowels, the nasality vs. orality of the preceding glide in [ṼṼ.G̃ṼṼ] vs. [VV.GṼṼN] explains this effect.

4.2.4 Nasal Harmony

Having confirmed that non-alternating pre-nasal [ṼṼN] vowels and contrastive /ṼṼ=CV/ vowels exhibit similar nasality 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-nasal [ṼṼN] and underlying contrastive /ṼṼ=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 penltimate vowels in the [VVGVV] sequence, respectively.

4.2.4.1 Nasal Harmony is Not Triggered by [ṼṼN]: Glides in pre-nasal [ṼṼN]

The results of the model comparing the glides in the contrastive /ṼṼ=CV/ and pre-nasal [ṼṼN] conditions are given in Table 6. The data in this model is limited to the thirteen speakers who categorically nasalize pre-nasal [ṼṼN] vowels in experiment 2; see the appendix for discussion of the remaining two speakers.

The model's intercept is the stem-final /ṼṼ/ vowel in the /ṼṼ=CV/ condition. Contrastive /ṼṼ/ 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 [ṼṼN] vowels are triggering nasal harmony.

The glide in the contrastive /ṼṼ=CV/ condition is significantly more nasalized than the contrastive /ṼṼ/ vowel that follows it (as is evident in Figure A5). The increased nasalance on the glide in contrastive [ṼṼ.GṼṼ] 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: 595). In any case, these results provide clear support for the claim that the glide in /VVGṼṼ=CV/ → [ṼṼ.GṼṼ=CV] strings is targeted for nasal harmony, triggered by the stem-final /ṼṼ/.

For glides in the pre-nasal [ṼṼN] condition, on the other hand, mean nasalance falls significantly below the mean nasalance of the contrastive /ṼṼ/ vowels in the /ṼṼ=CV/ condition (by 16.3%). The 95% confidence interval for the difference falls entirely outside (and below) the proposed *RoPE* (±.051), confirming they are less nasalized than final /ṼṼ=CV/ vowels. We therefore conclude that, unlike glides preceding contrastive /ṼṼ/ vowels, glides preceding a non-alternating [ṼṼN] vowel are not targets of nasal harmony.

Predictor	β	95% CI	*t*	*p*
Intercept (Final /ṼṼ/ in /ṼṼ=CV/)	.539	[.484, .594]	19.23	< .001 ***
glide (/ṼṼ=CV/ condition)	.065	[.048, .083]	7.36	< .001 ***
glide ([ṼṼN] condition)	-.163	[-.232, -.094]	-4.65	< .001 ***

Table 6: Results of the LMER model predicting nasalance across the glide in the [VVGVV] sequence for 13 speakers. CONDITION was included as a dummy-coded fixed effect. The final /ṼṼ/ in the /ṼṼ=CV/ condition serves as the intercept in the model, and the estimates for the other predictors describe the predicted deviation from the intercept.

4.2.4.2 Nasal Harmony is Not Triggered by [ṼṼN]: Penult stem vowels in pre-nasal [ṼṼN]

We now turn to a model comparing nasalance of the penultimate, pre-glide stem vowels in the pre-nasal [ṼṼN], oral /VV/, and contrastive /ṼṼ=CV/ conditions. The results of this model are summarized in Table 7. Here, penultimate oral vowels in /VV=CV/ serve as the intercept: the goal is to determine whether penultimate pre-glide vowels in the pre-nasal [ṼṼN] condition significantly differ from those in the oral /VV=CV/ condition.

The model estimates indicate that the penultimate pre-glide vowel in the contrastive /ṼṼ=CV/ condition is about 35% more nasalized than in the oral /VV=CV/ baseline. In the pre-nasal [ṼṼN] condition, the penult also differs significantly from the oral baseline, but only by approximately 7%. We computed a *RoPE* of ± .033 for penultimate oral vowels; the upper bound of the 95% CI for the oral-[ṼṼN] difference extends outside this region. Thus, while there is some evidence of nasalization on penultimate vowels in the pre-nasal [ṼṼN] condition, the amount of nasalization relative to those in the oral /VV=CV/ condition is about 27% smaller than the difference between the oral baseline and the contrastive /ṼṼ=CV/ condition.

Predictor	β	95% CI	*t*	*p*
Intercept (penult oral /VV/)	.192	[.131, .252]	6.25	< .001 ***
penult VV (ṼṼN)	.071	[.01, .132]	2.3	.03 *
penult VV (/ṼṼ=CV/)	.345	[.279, .412]	10.19	< .001 ***

Table 7: Results of the LMER model predicting nasalance across the penultimate, pre-glide stem vowel in the [VVGVV] sequence for 13 speakers who categorically nasalize pre-nasal [ṼṼN] vowels. CONDITION (penultimate stem vowel (oral /VV/, pre-nasal [ṼṼN], nasal /ṼṼ=CV/) was included as a dummy-coded fixed effect. The intercept is the penultimate stem vowel in the oral /VV/ condition.

4.2.5 Summary of results for Experiment 2

To summarize, non-alternating, pre-nasal [ṼṼN] vowels and contrastive /ṼṼ=CV/ vowels were not found to be significantly different in terms of nasality when uttered in the final position of a [VVGVV] sequence. Despite the similar surface nasality on the stem-final vowels in [ṼṼN] and contrastive /ṼṼ=CV/ conditions, pre-nasal [ṼṼN] and contrastive /ṼṼ/ triggered distinct patterns of nasalization across the preceding [VVG] sequence. The segments preceding the contrastive

/ṼṼ/ vowel were significantly nasalized across the entire span, to a similar degree as the /ṼṼ/ vowel itself. This confirms previous impressionistic descriptions that contrastive /ṼṼ/ vowels in Panjabi trigger leftward nasal harmony across [VVG] sequences, affecting both preceding vowels and glides (albeit optionally).

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

For the pre-nasal [ṼṼN] condition, nasalance is low on the glide [G], 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 [ṼṼN] sequence, which we analyze as the only phonologically nasalized segments in the [VVGṼṼN] string (setting aside the nasal consonant).

Nasalance on the penultimate vowel in [VVGṼṼN] was found to be significantly different from nasalance on the penultimate vowel in the oral condition /VVGVV=CV/. However, this difference is small in magnitude, only approximately 7.1%. These results suggest that the pre-nasal vowel in /VVN/ → [ṼṼN] is itself phonologically [+NAS], but does not trigger nasal harmony across the preceding glide and penultimate, pre-glide stem vowel in [VVGṼṼN]. 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.

4.3 Nasalization Reflects Harmony, not Coarticulation

4.3.1 Harmony is not an Artifact of Stress

A potential confound in our interpretation of nasalance values in the contrastive /ṼṼ=CV/ vs. pre-nasal [ṼṼN] conditions comes from stress placement. Stress has been described as weight sensitive in Panjabi, though in somewhat inconsistent terms (Bhatia 1993, Shackle 2003, Dhillon 2007, Bashir & Conners 2019, Hussain et al. 2019). Both syllables in the contrastive [ṼṼ=CV] condition are bimoraic, whereas, for pre-nasal [ṼṼN], 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 & Conners 2019), we might expect penultimate stress on [ˈṼṼ.G̃ṼṼ], and final stress on [VV.ˈGṼṼN].

Stress has also been found to correlate with increased nasality in some contexts and languages (e.g. Krakow 1989, Avelino et al. 2020, 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 /ṼṼ=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.[6]

[6] 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).

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 /ṼṼ=CV/ vs. pre-nasal [ṼṼN]. The penultimate and final stem vowels in the /ṼṼ=CV/ condition were 106 ms and 103 ms in mean duration, respectively, compared to a mean duration of 65 ms for the penultimate vowel and 151 ms for the final vowel in the pre-nasal [ṼṼN] condition. These measurements are at least consistent with the claim that contrastive /ṼṼ=CV/ and pre-nasal [ṼṼN] differ with respect to stress placement, stress being penultimate in the former case, and final in the latter. However, Bhatia (1993: 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: 21, 35). However, no such correlation, positive or negative, is present in our data. Considering all forms in the contrastive /ṼṼ=CV/ and /ṼṼ=NV/ conditions (including those that do not exhibit categorical nasal harmony), a Pearson's correlation analysis (r(723) = -.05, p = .22) between penultimate vowel duration and mean nasalance on the penultimate vowel did not detect a significant effect (Figure 10).

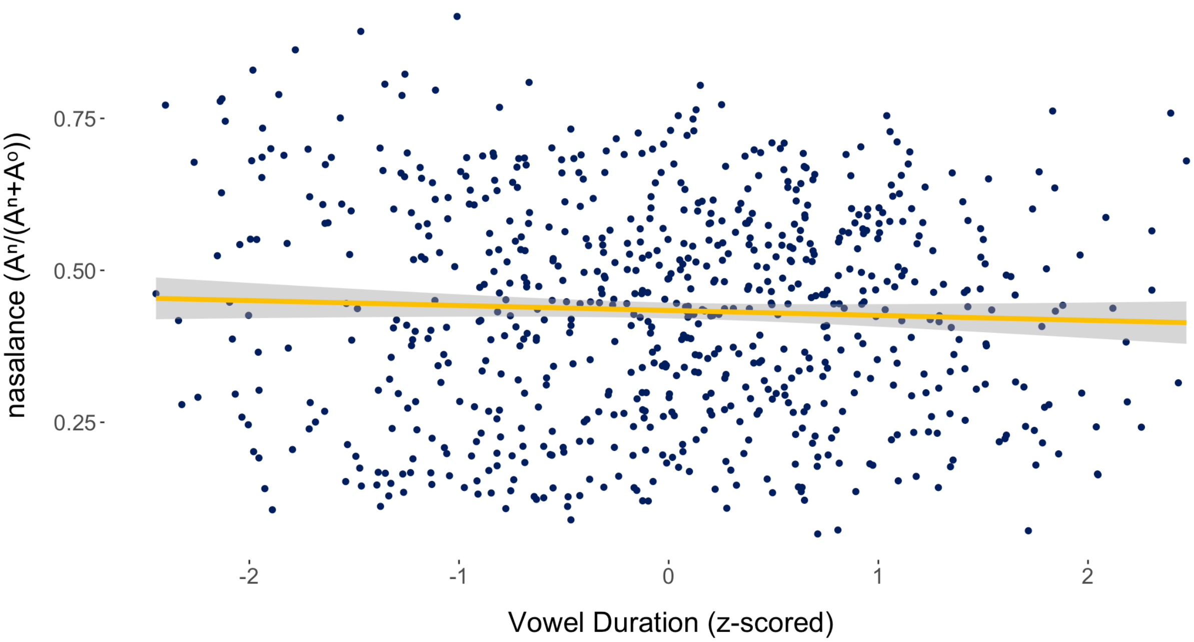

Figure 10: Scatterplot showing the estimated -.05 Pearson Correlation value between penultimate vowel duration and mean nasalance in the contrastive /ṼṼ=CV/ and /ṼṼ=NV/ conditions.

If the nasal harmony pattern observed in the contrastive /ṼṼ/ conditions 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 incongruent descriptions of Panjabi stress in prior literature, the uncertainty about the phonetic correlates of stress in the language, and the finding that nasalance on the penultimate pre-glide vowel in contrastive /ṼṼ=CV/ and /ṼṼ=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 nasality on the penults of contrastive /ṼṼ/ 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 vowel in contrastive /ṼṼ=CV/ in Panjabi, but not in pre-nasal [ṼṼN]. 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 /ṼṼ=CV/ condition, but not from predictable, contextually nasal vowels in the [ṼṼN] condition.

An alternative analysis of this data might be possible in which nasalization in contrastive /ṼṼ=CV/ owes to a coarticulatory window in which the velum is lowered for a more or less fixed period of time. Assume that in both [ṼṼ.G̃ṼṼ] and [VV.GṼṼN] 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.GṼṼN] than in [...ṼṼ.G̃ṼṼ], because the additional, word-final nasal segment in [...VV.GṼṼN] 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 /ṼṼ=CV/ often yields nasalized [ṼṼG̃ṼṼ], but outcomes in which harmony fails to apply [VVGṼṼ] 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 /ṼṼ=CV/ is quite puzzling. On the other hand, if nasal harmony is an abstract phonological process, then categorical variation between nasalized [ṼṼG̃ṼṼ] and non-nasalized [VVGṼṼ] can be straightforwardly analyzed as optional rule application (see also Plug et al. 2019).

Second, in section 4.3.1 we observed that there is no correlation between the duration of the penultimate pre-glide vowel in contrastive /ṼṼ/ 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 [ṼṼG̃ṼṼ] (e.g. Solé 1992, 1995).

A third argument against this approach comes from the analysis of a condition in our data which we have not yet discussed: contrastive /ṼṼ/ vowels followed by a nasal-initial postposition, /ṼṼ=NV/.

If contrastive /ṼṼ/ 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 /VVGṼṼ/. Conversely, if the consistent nasalance in the /ṼṼ=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 /ṼṼ=NV/ should mirror the nasalance pattern of the pre-nasal [ṼṼN] condition: there should be no evidence of harmony.

Each item in the /ṼṼ=CV/ condition was also produced in a corresponding /ṼṼ=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 /ṼṼ=NV/ condition is provided in Figure 11, alongside the baseline oral /VV/ and contrastive /ṼṼ=CV/ conditions for comparison.

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

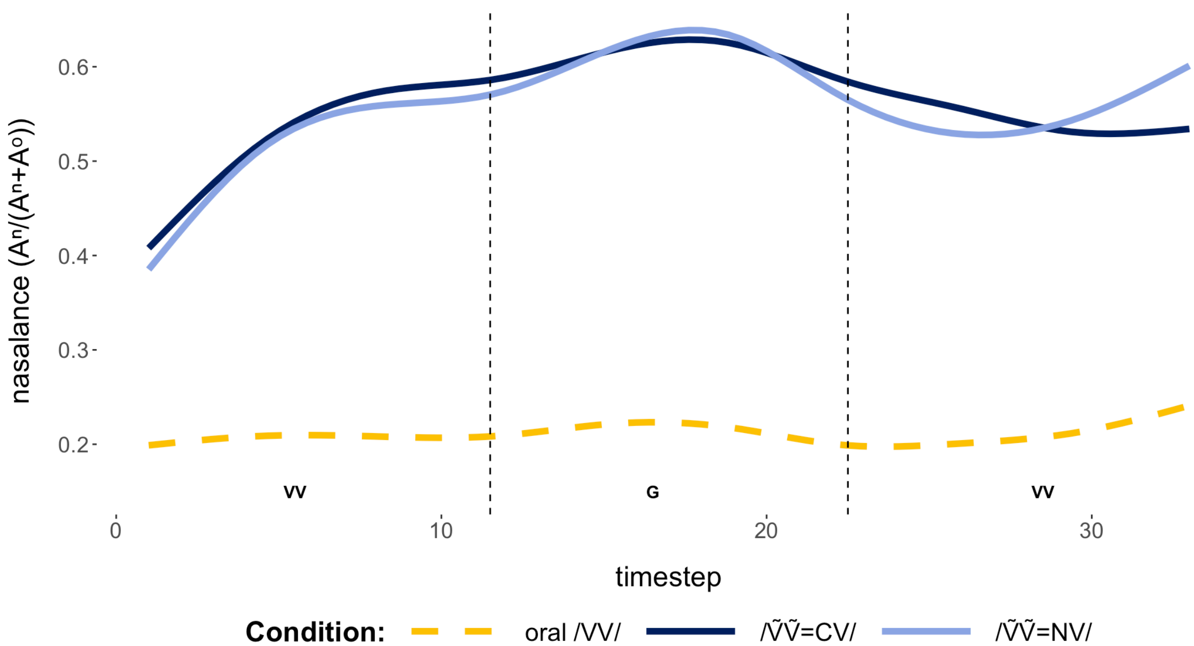

Figure 11: GAM curves comparing the constrastive /ṼṼ=NV/ condition to the oral /VV/ and contrastive /ṼṼ=CV/ conditions. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VVGVV] sequence for each condition for all fifteen speakers.

A pairwise comparison between the penultimate vowels in the /ṼṼ=CV/ and /ṼṼ=NV/ conditions in table 8 shows that the mean nasalance of the penultimate vowel in the /ṼṼ=NV/ condition is not significantly different from the mean nasalance of the penultimate vowel in /ṼṼ=CV/.

Predictor	β	95% CI	*t*	*p*
Intercept (Penult VV in /ṼṼ=CV/)	.533	[.460, .607]	14.24	< .001 ***
Penult VV in /ṼṼ=NV/	-.035	[-.122, .052]	-.79	.44

Table 8: Results of the LMER model predicting nasalance across the penultimate vowel in the [VVGVV] sequence for 15 speakers. CONDITION (penultimate vowel (/ṼṼ=CV/) and penultimate vowel (/ṼṼ=NV/)) was included as a dummy-coded fixed effect. The intercept is the penultimate vowel in the /ṼṼ=CV/ condition.

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 straightfowardly consistent with a phonologically-controlled, optional harmony process which spreads nasality leftward from contrastive nasal vowels /ṼṼ/, but not from derived, predictable pre-nasal [ṼṼN] vowels.

4.5 Summary of Experiment 2

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

5 Discussion

5.1 Analyzing [ṼṼN] vowels in Panjabi with abstract URs

The above experiments established several facts about non-alternating [ṼṼN] vowels in Panjabi. First, these vowels are phonologically nasal on the surface. Their realization mirrors the categorical nasality of contrastive /ṼṼ/ vowels in both experiments, and changes in speech rate do not impact the degree of nasalization on [ṼṼN]. Nonetheless, derived nasal vowels in [ṼṼN] differ from contrastive nasal vowels in /ṼṼ=CV/ and /ṼṼ=NV/ in failing to trigger leftward nasal harmony: /VVGṼṼ/ → [ṼṼ.G̃ṼṼ], but /VVGVVN/ → [VV.GṼṼN], *[ṼṼ.G̃ṼṼN] (experiment 2).

The interaction between nasal harmony and [ṼṼN] 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 & 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 (3) produces an opaque interaction between nasal harmony and the contextual nasalization of pre-nasal vowels in /VVN/ → [ṼṼN] (which we dub 'assimilation' in (3)). In (3a), the word-final nasal vowel /ɑ̃ɑ̃/ 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 /ɑ̃ɑ̃/ in /sɑɑʋɑ̃ɑ̃/ → [sɑ̃ɑ̃ʋ̃ɑ̃ɑ̃], as desired.

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

		a. /sɑɑʋɑ̃ɑ̃/	b. /ɑɑʋɑɑm/
Harmony:	$\text{[-CONS]} \longrightarrow \text{[+NAS]}/\_\_X_{0\,[\text{-CONS}]}V_{[\text{+NAS}]}$	sɑ̃ɑ̃ʋ̃ɑ̃ɑ̃	-
Assimilation:	$V \longrightarrow \text{[+NAS]}/\_\_C_{[\text{+NAS}]}$	-	ɑɑʋɑ̃ɑ̃m
		[sɑ̃ɑ̃ʋ̃ɑ̃ɑ̃]	[ɑɑʋɑ̃ɑ̃m]

In (3b), the [ṼṼN] vowel is underlyingly oral, /ɑɑʋɑɑm/. Since harmony is the first rule to apply, it cannot 'know' that the final vowel of /ɑɑʋɑɑm/ will eventually be nasalized by the assimilation rule in (3) — harmony is only sensitive to underlying nasality, not derived, predictable nasality. As such, harmony fails to apply to /ɑɑʋɑɑm/. The underlying form /ɑɑʋɑɑm/ subsequently undergoes assimilation, producing the surface form [ɑɑʋɑ̃ɑ̃m]. This is a textbook case of counterfeeding opacity: assimilation applies 'too late' in the derivation to feed nasal harmony (e.g. Kiparsky 1976, Baković 2011).

To reiterate a crucial aspect of our analysis, underlying representations like /ɑɑʋɑɑm/ are *covert* in Panjabi, because pre-nasal vowels in non-alternating morphemes never actually surface as oral. The use of covert URs is a centerpiece of the analysis in (3): it is the key to distinguishing between derived (predictable) and contrastive (unpredictable) nasality for the purposes of determining when nasal harmony applies.

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

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 et al. (1978): asked to pluralize the proper name *Bach* [bɑx], English speakers will uniformly provide [bɑx-s], as opposed to any of the other plural forms conceivably suggested by the vocabulary of English (*[bɑx-z], *[bɑx-ɪz], *[bɑɣ-z], *[bɑx-en], 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] $\rightarrow$ [αVOI]/[-SON, αVOI]__# ; Halle et al. 1978).

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. Pierrehumbert 2006, Kirchner et al. 2010, Kirchner 2011, Kaplan 2015, Pierrehumbert 2016, Goldrick & Cole 2023, Du & Durvasula 2025).[7] 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. (e.g. Albright & Hayes 2003, Becker et al. 2011, Daland et al. 2011, Becker et al. 2012, Gorman 2013, Gouskova & Becker 2013, Becker et al. 2017, Du & Durvasula 2025).

Perhaps more to the point, we are unaware 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 (3) (see also Kawahara 2001, Ettlinger

[7] An infamous exception is the 'English past-tense debate'; see e.g. Pinker (2002), Seidenberg & Plaut (2014). We note that this is a debate about morphological patterning (with phonological conditioning, Albright & Hayes 2003), where here we are concerned with purely phonological patterns.

2008, 2009). 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 & 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 /ṼṼ/ and pre-nasal [ṼṼN] in Panjabi. Consequently, no form of averaging over stored exemplars will produce an abstract difference between contrastive /ṼṼ/ and pre-nasal [ṼṼN] 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 /ṼṼ/ triggers harmony, but pre-nasal [ṼṼN] 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 & 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 /ʁaːd/ → [ʁaːˑt] 'wheel' is slightly longer, phonetically, than the vowel in /ʁaːt/ → [ʁaːt] 'council'. In exemplar models, the slight lengthening of the vowel in [ʁaːˑt] 'wheel' can be attributed to influence from the plural form [ʁɛːˑd-ɐ] 'wheels', where the vowel is transparently lengthened before voiced [d]. No such influence exists for [ʁaːt] 'council', which has the plural form [ʁɛːt-ə] 'councils' (see also Kaplan 2017, Braver 2019).

Incomplete neutralization is a kind of phonetic opacity: singular [ʁaːt] 'wheel' opaquely inherits the vowel length of plural [ʁɛːd-ɐ] 'wheels', where lengthening is phonetically transparent. (This bears a close resemblance to the generative mechanism of OUTPUT-OUTPUT FAITHFULNESS, 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 [ṼṼN].

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

For suffixed forms like [lɛɛ-jɑ̃ɑ̃ɳ] 'take-INF.OBL', one could appeal to influence from a non-nasalized, related form of the stem vowel ([lɛɛ-jɑɑ] 'take-IMP') to explain why harmony fails to apply in [lɛɛ-jɑ̃ɑ̃ɳ]. However, this explanation also falls short, because it equally — and again, incorrectly — predicts that nasal harmony should be inhibited in suffixed forms containing a *contrastive* nasalized vowel in the suffix, such as [mətʃii-ʋɑɑ] 'fisherman' vs. [mətʃĩĩ-j̃ɑ̃ɑ̃], *[mətʃiiją̃ą̃] 'fish-PLURAL'.

A third potential mechanism for producing opacity in /VVGVVN/ → [VV.GṼṼN], *[ṼṼ.G̃ṼṼN] 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-nasal /VVGVVN/ → [VV.GṼṼN] is influenced by *oral* [VV.GVV], that influence could inhibit harmony in the penult of [VV.GṼṼN], in order to maintain consistency in the nasality of the penultimate vowel.

The obvious question here is why pre-nasal /VVGVVN/ → [VV.GṼṼN] should be influenced by oral [VV.GVV], specifically. Indeed, forms with contrastive nasal vowels, [ṼṼ.G̃ṼṼ], are at least equally plausible candidates for influencing pre-nasal [VV.GṼṼN] 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-nasal /VVGVVN/ → [VV.GṼṼN] is in some sense more closely related to oral [VV.GVV] than contrastively nasal [ṼṼ.G̃ṼṼ] (see also McCarthy 1999 on sympathy theory).

Fourth, it is possible that the distinction between pre-nasal /VVGVVN/ → [VV.GṼṼN] and contrastive [ṼṼ.G̃ṼṼ] is simply an artifact of historical change. Presumably, pre-nasal assimilation developed *after* the emergence of nasal harmony, thus yielding an opaque synchronic interaction between the two processes. Speakers might simply memorize forms like [mətʃĩĩ-j̃ãã] 'fish-PLURAL' vs. [lɛɛ-jããɳ] '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. While we have not carried out wug-testing, 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, *[G̃ṼṼN], which bans a nasalized glide before a nasalized (long) vowel, followed by a nasal consonant. The trigram constraint *[G̃ṼṼN] straightforwardly excludes unattested *[ṼṼG̃ṼṼN] sequences while allowing [ṼṼG̃ṼṼ]. Furthermore, it does so with reference to surface forms alone: this renders the lack of *[ṼṼG̃ṼṼN] sequences transparent, rather than opaque, and thus vitiates the need for abstract underlying representations. Within an exemplar-theoretic framework, a constraint like *[G̃ṼṼN] 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 constraints over segmental sequences quickly becomes intractable as the length of those sequences increases (Hayes & 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. For example, Hayes & 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 *[G̃ṼṼN] of course goes beyond these limitations.

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 makes it difficult–if not impossible–to distinguish between principled phonotactic gaps and accidental ones (Chomsky & Halle 1965, Hayes & White 2013, Wilson & Gallagher 2018). Principled gaps are those which native speakers judge to be ill-formed, whereas accidental gaps are unattested but fully acceptable to speakers. A statistical learner, lacking a mechanism for making this distinction, would be just as likely to form constraints that exclude acceptable but unattested forms as it would be to discover true phonological generalizations.

To test the extent to which such overgeneration 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 from 5,351 webpages in 2017 written in Shahmukhi script, the standard orthography for 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 in the following manner. We then extracted the complete set of unique Shahmukhi characters from the corpus and transliterated 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 [pəɾ] 'but, yet' is most often written with two characters in Shamukhi, omitting the short vowel: پر. Our script transliterated this word as <#pɾ#>, 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, ی may represent /j/ or /iː/ and و may represent /ʊ/, /uː/, /oː/, or /ɔː/. 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 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 – and native speaker consultants uniformly judge [lɑ̃ɑ̃l] to be a fully acceptable, though unattested, word. Additionally, smaller bigram [LṼṼ] (type frequency 1,602) and [ṼṼL] (type frequency 8) 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), and that nasal vowels separated by other consonants are attested (e.g., type frequency of 7 for [ṼṼOṼṼ]), this gap likewise lacks an obvious phonetic grounding.

While future work on an annotated corpus of Pakistani Punjabi is needed to confirm these results, 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. Burzio 1996, Scobbie et al. 1996, Hayes 1999, Albright 2002, Cole & Hualde 2011, Allen & Becker 2015, Wang & Hayes 2025, and various others; cf. Krämer 2012, Bowers 2015, Bermúdez-Otero 2018, Hyman 2018 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. 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' (4).

(4) Counterfeeding opacity in Berbice Dutch Creole

		/nimi-tɛ/
Place assimilation:	C[+NASAL] ⟶ [αPL]/__ [αPL,-CONT,-SON]	–
Vowel deletion:	V ⟶ ∅/__]$_{\text{STEM}}$–$_{\text{SUFFIX}}$[	[nim-tɛ]
		[nim-tɛ]

As in the rule-based analysis of Panjabi nasal harmony (3), 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).[8]

[8]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.

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 (5b) specifically bans changes in place of articulation between a morphological base like [nimi] and a corresponding inflected form like [nim-tɛ] (5). Importantly, OO-FAITH constraints refer only to the *surface* forms of bases and their morphological derivatives.

The simplified tableau in (5c) 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.

(5) 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 𝔹-𝔸, where 𝔹 is a morphological base and 𝔸 an affix, in which the 𝔹 substring of 𝔹-𝔸 contains a segment which differs in place of articulation from the corresponding segment in the base form 𝔹.

c.

[nimi-tɛ] / BASE: [nimi]	OO-IDENT-PLACE	NT PLACE ASSIMILATION
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. Wolf 2008, Bermúdez-Otero 2011, Trommer 2013, Mascaró 2016). 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 (5).

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 [dʒəʋãã̃ɳ], *[dʒə̃ʋ̃ããɳ] 'youth, soldier' in Panjabi. The root [dʒəʋããɳ] has no morphological base to be faithful to; hence, output-oriented mechanisms for producing opacity fall short of explaining why [dʒəʋããɳ] 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 & 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 & 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 & Kisseberth (1995). Harmony is illustrated in (6a), in which we indicate nasal harmony domains by means of parentheses.

(6) Nasal harmony in Máíhĩki

a. Long-distance rightward nasal spreading from contrastive /Ṽ/:
/sẽje/ → (sẽj̃ẽ) '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 (6b).[9] Cole & Kisseberth (1995) analyze this contrast by assuming that contrastively nasal vowels initiate harmony domains that must spread as far to the right as possible (6a), while nasal consonants initiate harmony domains that only need spread as far as the rightmost syllable boundary (6b).

Crucially, Cole & 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], *[nãj̃ĩ] on analogy with [sẽj̃ẽ], in which nasal harmony is initiated by an underlying nasal vowel (6a). 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.

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. In addition, several approaches (e.g. Pater et al. 2012, O'Hara 2017, Rasin & Katzir 2018, Paramore 2025, Wang & Hayes 2025) 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 & Smolensky 1993/2004). Lexicon optimization amounts to the proposal that, in

[9] Sylak-Glassman et al. (2014) argue that post-nasal vowels are oral rather than nasal in Máíhĩki; this does not affect our discussion.

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 /ṼṼN/ for non-alternating pre-nasal vowels in [ṼṼN]. We have argued that this is incorrect: surface [ṼṼN] is systematically analyzed as underlying /VVN/, even in the absence of alternations (see also McCarthy 2005b, Nevins & Vaux 2007, Krämer 2012, Rasin & 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 [ṼṼN] ← /VVN/. If /VVGṼṼN/ were a potential underlying form, we would expect to see at least some cases of pre-nasal vowels triggering harmony in [VV.GṼṼN]; the absence of such examples seems telling.

It could be that underlying /ṼṼN/ is disallowed in Panjabi as the result of a morpheme structure constraint on underlying forms (e.g. Booij 2011). Alternatively, Panjabi learners might adopt a learning strategy that systematically rejects /ṼṼN/ as a string in *actual* URs, without directly banning underlying /ṼṼN/ by means of a morpheme structure constraint or other grammatical mechanism (see also Stampe 1973, McCarthy 1998). 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-nasal 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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Appendix

Experimental items

Condition 1 - CVV		Condition 2 - CṼṼ		Condition 3 - CVVN	
bɑɑt	'story'	bɑ̃ɑ̃	'arm'		
		bɑ̃ɑ̃k	'early teen'	pɑɑn	'Betel nut chewing'
bii	'seed'			biin	'a musical instrument'
boo	'smell'				
piiɖ	'pain'	pĩĩg	'swing'		
poo	'12th Panjabi month'	põõtʃ	'arrival'	koon	'who'
dɑɑ	'strategy (wrestling)			dɑɑm	'price, money'
dɑɑk	'post'	dɑ̃ɑ̃g	'big stick'		
ɖeeɖ	'one and a half'				
doo	'two'			doon	'ropes on a knit bed'
dʒii	'family member'				
		dʒõõ	'barley'		
dʒoog	'coming together'	dʒõõk	'leach'		
		dʒũũ	'louse'	dʒuun	'June'
tɑɑ	'warmth, fever'	tɑ̃ɑ̃	'that; so that'	tɑɑn	'melody'
tʰɑɑ	'was'	tʰɑ̃ɑ̃	'place, room'	tʰɑɑn	'a bolt of cloth'
tɔɔk	'yoke, iron collar'			tɔɔɳ	'neck'
tʃɑɑ	'desire, wish'	tʃʰɑ̃ɑ̃	'shade'	tʃʰɑɑn	'non-refined flour'
ruup	'beauty'	rũũ	'cotton'	luun	'salt'
sɑɑ	'breath'				
seek	'warmth'	sẽẽk	'termite'		
sii	'sew.IMP'			siin	'ploughing'
sɔɔ	'hundred'	sɔ̃ɔ̃	'sleep.IMP'	sɔɔɳ	'rainy season'
suud	'profit, interest'	tũũ	'you'		
		ʋɑ̃ɑ̃g	'like, similar'	ʋɑɑn	'strings of a knit bed'
gɑɑl	'abuse'	gɑ̃ɑ̃	'cow'		
kɑɑdʒ	'button-hole'	kɑ̃ɑ̃	'crow'	kʰɑ́ɑ́n	'a proverb'
kuuk	'melodious sound'	kũũdʒ	'black sparrow'		
kʰuu	'a well'	kʰũũdʒ	'a corner, angle'	xuun	'blood'
xɑɑb	'dream'			xɑɑntʃaa	'corner, trick'

Figure A1: Experiment 1 tokens, consisting of 63 monosyllabic words separated into three groups: oral vowels (CVV), nasal vowels (CṼṼ), and /VVN/ vowels (CVVN).

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

Oral Condition - CVVGVV

sət-ɑɑjii	seven-twenty	ɔɔlii-jɑɑ	pious man-PL
həʋɑɑ	air	tʃoo-ʋii	four-twenty
pɑɑʋee	cot leg	beeʋɑɑ	a widow
dəʋɑɑ	medicine, remedy	tɑɑʋuu	father's oldest brother
mʊkʰiijaa	chief	ʋəkʰɑɑʋee	boasting

Nasal Condition - CVVGṼṼ

tʃɑ̃ɑ̃ʋ̃ẽẽ	pumicestone	ũũ-ʋẽẽ	that-way
dõõ-ʋɑ̃ɑ̃	two-way	kĩĩ-ʋ̃ẽẽ	what-way
ɛ̃ɛ̃-ʋ̃ẽẽ	this-way	mətʃĩĩ-jɑ̃ɑ̃	fish-PL
sɑ̃ɑ̃-ʋ̃ɑ̃ɑ̃	breath-PL	tĩĩʋ̃ĩĩ	a woman, wife

/VVN/ Condition - CVVGVVN

dʒəʋɑ̃ɑ̃ɳ	youth, soldier	ədʒəʋɑ̃ɑ̃ɳ	omum seed
siijɑ̃ɑ̃ɳ	recognition	teejɑ̃ɑ̃ɳ	attention
lɛɛ-jɑ̃ɑ̃ɳ	take-INF.OBL	ɑɑʋɑ̃ɑ̃m	general public

Figure A2: Experiment 2 tokens, consisting of 24 di- and trisyllabic words separated into three groups: oral /VV/, contrastive nasal /ṼṼ/, and pre-nasal vowels /VVN/.

decline in waveform amplitude in the oral channel. A sample annotation is provided in figure A3.

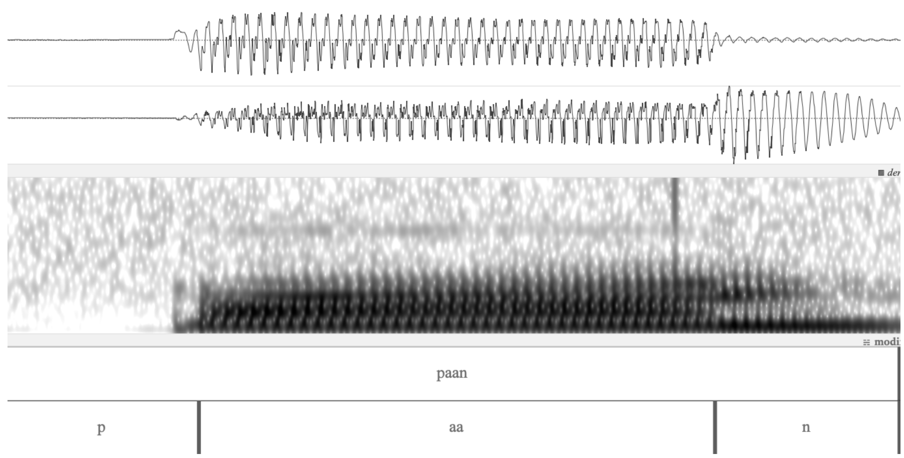

Figure A3: Spectrogram and waveform showing a sample annotation for /pɑɑn/ for speaker AR0. The top waveform shows amplitude for the oral channel, and the bottom shows amplitude for the nasal channel.

For almost all of the CṼṼ 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 /ṼṼ/ 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. Desmeules-Trudel & 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 /ṼṼ/ vowel when these intrusive nasal consonants were present. To avoid corrupting the reported nasality of the /ṼṼ/ 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 A4.

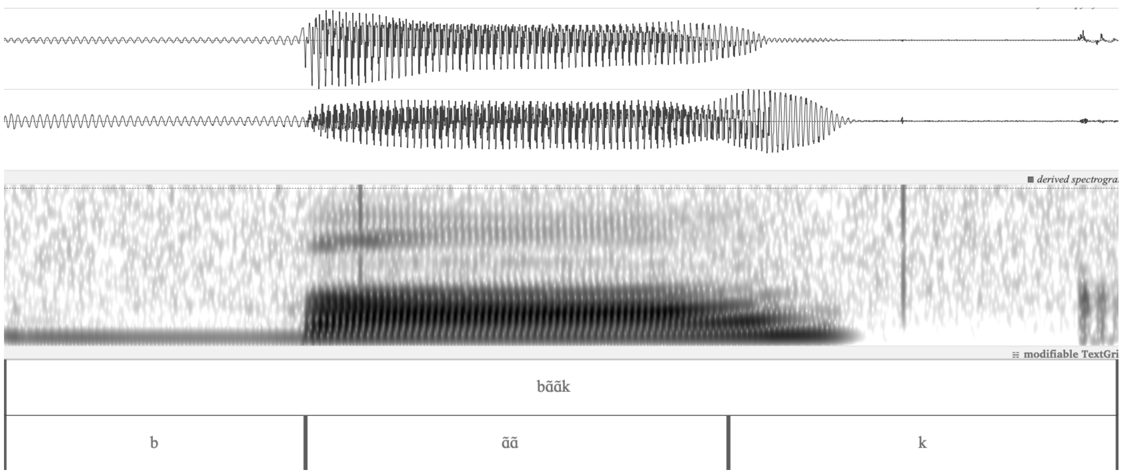

Figure A4: Spectrogram and waveform showing the intrusive [ŋ] in /bããk/ for speaker AK2.

Nasalization in Lahori Panjabi

In section 4.2 we noted that two speakers in Experiment 2 produced /VVN/ vowels with anticipatory coarticulation rather than categorical nasality. GAM curves across [VVGVV] sequences are displayed in figure A5 for these two speakers. As can be seen by the curves, nasalance across the penultimate vowel and glide for the /VVN/ condition is proportionally similar to the oral /VV/ condition, but a cline-like increase in nasalance begins near the onset of the /VVN/ vowel, only nearing the nasalance level of the /ṼṼ=CV/ condition at the offset of the [VVGVV] 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.

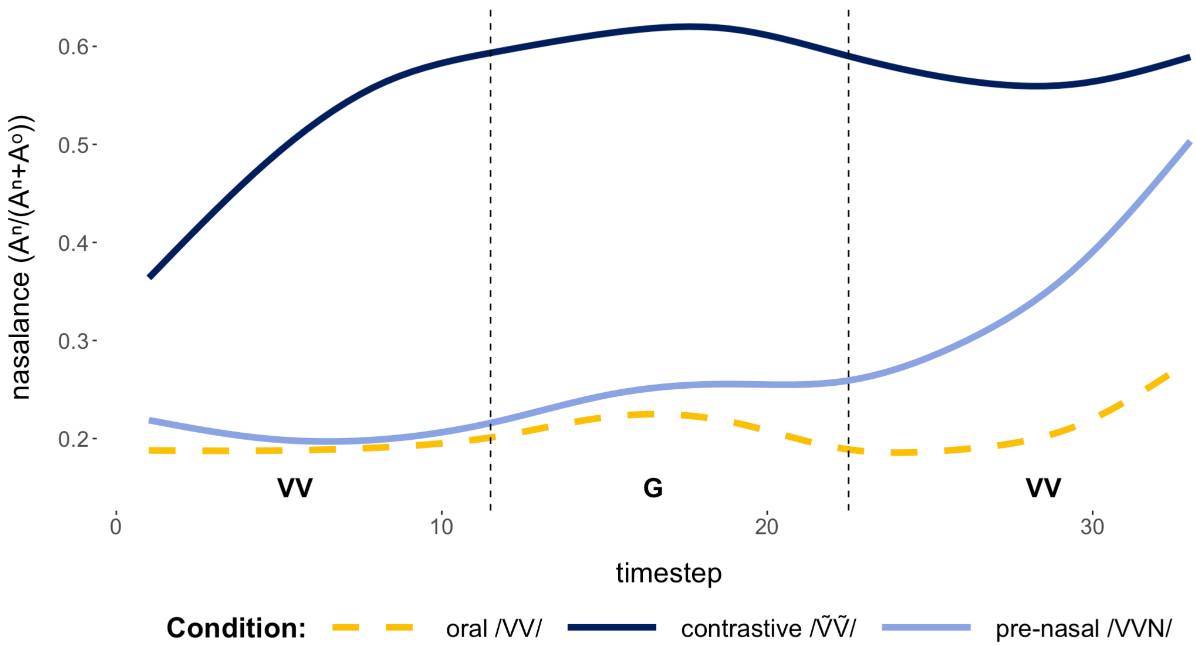

Figure A5: GAM curves for the oral /VV/, contrastive /ṼṼ=CV/, and /VVN/ conditions. Curves visualize the mean vowel nasalance at 33 normalized timesteps across the [VVGVV] sequence for the two speakers that exhibit coarticulatory nasality on /VVN/ vowels.