Guaraní Voiceless Stops in Oral versus Nasal Contexts: An Acoustical Study

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This acoustic study investigates voiceless stops in Guaraní that are described as transparent to nasal harmony. Voiceless stops in oral versus nasal contexts are examined in relation to theoretical issues of locality and phonetic implementation. First, the oral/nasal and voicing properties of the stops are considered in connection to proposals in phonological theory that feature spreading produces strictly continuous spans of a spreading property. The stops are discovered to display the acoustic attributes of voiceless oral obstruents; no evidence of nasal airflow energy was observed during closure nor was the closure fully voiced. These results suggest that strict continuity of a spreading featural property is not always found in the phonetic output. Second, the timing of the voicelessness is addressed. Interestingly, the duration of voicelessness of the stops [p, t] remains the same across oral/nasal environments, although the voiceless interval shifts to persevere longer into the following vowel in nasal contexts. The velar stop does not exhibit an increased perseverance of voicelessness after closure release—it displays the longest VOT of all places of articulation, and its VOT remains unaffected by oral/nasal context. It is suggested that incorporating a notion of conflicting realizational requirements in models of phonetic implementation is important in interpreting these results.

1. Introduction

1.1 Feature spreading in phonological theory

A current controversy in the study of phonological feature spreading concerns the theoretical treatment of transparent segments. Transparent segments are those that appear to be unaffected by the spreading of some feature or gesture, but they do not prevent the element from spreading to further segments. An example of segment transparency occurs in the consonant harmony of Chumash, a Hokan language once spoken in Southern California. In Chumash consonant harmony, coronal fricatives agree in tongue blade/tip orientation features through a regressive spreading of these properties. This harmony produces alternations in the quality of coronal fricatives under suffixation, as shown in (1) (data are from Shaw 1991). All other segments are characterized as transparent in this process, since they are apparently unaffected by the spreading.

(1) Chumash coronal consonant harmony

a.	/k-sunon-us/	[ksunonus]	'I obey him'
	/k-sunon-ʃ/	[kʃunonʃ]	'I am obedient'
b.	/ha-s-xintila/	[hasxintila]	'his indian name'
	/ha-s-xintila-waʃ/	[haʃhintilawaʃ]	'his former indian name'

The issue raised by these data is whether transparent segments must be regarded as skipped by the feature spreading or whether the relevant property can be understood as actually carrying through the segment. If feature spreading skips a segment, this presents a case of 'action-at-a-distance,' where a feature spreads between non-adjacent segments without becoming a property of intervening segments. In the case of coronal consonant harmonies like the above, recent work by Gafos (1996, 1997), Ní Chiosáin and Padgett (1993, 1997), and Flemming (1995) has argued against a skipping approach. Typological studies by these researchers reveal that the coronal consonantal features which appear to spread at a distance are precisely those that do not affect the perceived acoustic quality of the intervening segments; hence there is no need to posit that the transparent segments create discontinuities within the spreading domain of the tip/blade gesture. These studies make a compelling argument for eliminating the notion of action-at-a-distance in feature spreading, at least in coronal harmonies, since the relevant gesture can be conceived of as being sustained throughout the spreading span (though in the majority of these languages the actual posture of the tip/blade during transparent segments remains to be instrumentally verified).

Research on certain other cases of segmental transparency supports extending this viewpoint beyond coronal consonant harmonies. In a study of transparent consonants in vowel harmony, Ní Chiosáin and Padgett (1997) argue that the consonants in question actually undergo vocalic feature spreading but may be perceived as transparent because the consequences of the spreading property are small in terms of contrast potential for these segments. Building on Cohn (1990, 1993a) and Ohala and Ohala (1993), among others, Walker and Pullum (1999) present evidence that a velum lowering gesture carries through transparent glottal stops in nasal harmony. See also studies by McCarthy (1994) and Padgett (1995). The broader issue confronting the theory is whether all segment transparency can be subsumed under this mode of explanation, that is, that perceived transparent segments are compatible with concurrent production of the spreading property.

For two familiar kinds of transparent segments, it remains to be established whether this is a viable approach; these are (i) transparent vowels in vowel harmony (but see Ní Chiosáin and Padgett 1997), and (ii) buccal obstruents described as transparent in nasal harmony—buccal obstruents being those articulated forward of the point where the velic valve joins the oral and nasal cavities. The present study focuses on the latter case: it brings an investigation of transparent buccal stops in nasal harmony to bear on the hypothesis that a spreading featural property permeates through transparent segments. This research examines the acoustic properties of intervocalic voiceless stops in oral versus nasal contexts in Guaraní. Guaraní is an Amazonian language well-known for its nasal harmony in which all voiced segments become nasalized. Phonological descriptions report that voiceless segments exhibit transparent behavior in the nasal harmony, that is, voiceless obstruents remain oral but do not block nasality spreading (Gregores and Suárez 1967; Rivas 1974). An acoustic comparison of oral and nasal word pairs in Guaraní provides information about what effect, if any, nasal harmony has on 'transparent' voiceless stops. Transparency in nasal harmony forms an important test case for the notion that transparency can be reduced to a lack of perceptual consequences for the transparent segment, because nasalization audibly affects both vowels and buccal consonants. If the result of nasality spreading is a single and continuous gesture of velum lowering, then it is expected to impact all segments within the nasality span.

From a typological perspective, nasal harmony patterns in which voiceless stops are reported to exhibit transparent behavior are well-attested. An overview of segment patterning in nasal harmony is given in Table 1, based on a cross-linguistic survey by Walker (1998). The survey reveals that sonorant segments, i.e. vocoids and liquids, pattern in one of two ways, they are either targets (become nasalized) or they block spreading. Obstruents are also opaque in some languages, but when they do not not block nasality spreading, they display a somewhat different range of outcomes. A portion of them—typically voiced segments—become nasalized, while the remainder—typically voiceless—are described as transparent. Guaraní presents an example of this latter kind. For a formal analysis of the typological generalizations and segment patterning in nasal harmony, see Walker (1998). The focus here is on the realization of transparent segments and their bearing on certain theoretical approaches to transparency. Although instrumental research has been performed on languages in which voiceless stops block nasality spreading (Cohn 1990, 1993a; Gerfen 1996), we are not aware of any instrumental study of Guaraní that has investigated the nature of voiceless stops that are reported to be transparent in nasal harmony, or for that matter, in any of the languages reported to display this phenomenon.[1] Under conditions of nasalization, it is conceivable that segments normally produced as voiceless stops might be realized as voiceless nasals or even as voiced nasal stops. Moreover, if the continuous velum lowering gesture produced by nasality spreading were viewed as requiring only that the velum accomplish some minimal degree of opening, then it is conceivable that during the stop there would be no significant perceptual acoustic coupling of the oral and nasal cavities nor sufficient nasal airflow to produce audible turbulence in the nasal cavities (on the acoustic requirements of nasality see Bell-Berti 1993). However, the leakage of air through the velar port could be sufficient to induce voicing by enabling transglottal airflow that produces the necessary drop in transglottal pressure (see Hayes 1995 and citations therein).

The present acoustical study asks two questions about the realization of Guaraní 'transparent' stops in nasal harmony:

(2) i. Within nasal spreading spans are voiceless stops in fact realized as transparent (i.e. oral) obstruent stops or are they nasal stops of some kind (i.e. produced with the usual acoustic patterns of audible nasals)?

ii. If voiceless stops are indeed transparent, what effect, if any, does nasal harmony have on the voicing timing properties of these stops?

This study is based on work with one language consultant. Although it would be preferable to have more subjects, given the understudied nature of Guaraní and the limited availability of consultants, this work makes a unique contribution to the phonetic documentation of this language. It also forms groundwork for future research on Guaraní nasalization.

The broader aim of this research is to utilize instrumental study to test three hypotheses regarding locality and the outcome of feature spreading that have emerged due to recent work in theoretical phonology. Ní Chiosáin and Padgett (1993, 1997) propose Strict Segmental Locality. This posits that <u>all</u> spreading must occur between segments adjacent at the level of the root node—spreading may not skip a segment. Gafos (1996) proposes a connected notion referred to as Articulatory Locality, which requires that feature spreading not produce a span for the spreading gesture containing discontinuities (i.e. interruptions).

The aim of these restrictive views of locality is to account for the limited transparency effects observed in feature spreading. As mentioned above, many cases of putative transparency can be reduced to a lack of perceptible effect on the transparent segment. Further, these researchers note that transparency is typically not found in instances where the spreading property is expected to have a significant perceptual impact on the intervening segment (though vowel and nasal harmony present possible counter-examples). While the Strict Segmental Locality and Articulatory Locality proposals have some subtle distinctions, these points of difference will not affect the point to be examined here: whether there are any indications from the acoustic record that the property of velic opening carries through transparent segments in the phonetic output of nasality spreading.

The possible phonetic outcomes for transparent segments can be subsumed under three general hypotheses, schematized in Figures 1-3. These illustrations focus on the sequence of velum postures involved in a given utterance, schematizing the possible outcomes of a perseverative spreading of nasality from an initial nasal stop. The first hypothesis (H1) is that feature spreading sustains full velum lowering throughout the spreading span, producing perceptible nasalization in buccal stops. This is schematized in Figure 1 for an utterance [mẽnã], where a single wide velum lowering posture continues through the entire sequence of segments. This outcome is referred to as <u>full nasalization</u>, and it is consistent with the proposals of Strict Segmental Locality and Articulatory Locality.

As noted above, a second plausible outcome exists. If the continuous velum lowering that results from nasal harmony is viewed as accomplished provided there is a sustained posture of at least minimal velic opening, then the utterance could be produced as in Figure 2, where a minimal degree of velic opening during the coronal stop induces voicing but no audible nasalization, i.e. /meta/ → [mẽdã]. This hypothetical outcome (H2) will be referred to as the <u>nasal leak configuration</u>. Though nasalization would not provide an acoustic cue to this articulatory state, nasal leak is predicted to be apparent from the presence of voicing during the stop. The nasal leak alternative is again compatible with both Strict Segmental Locality and Articulatory Locality: the spreading property is understood as requiring that a continuous minimal threshold of velic opening be met.

A third alternative (H3) is the one suggested by the phonological descriptions of Guaraní, namely, that voiceless stops in nasal harmony are produced as true voiceless oral obstruents. If this is indeed the case, then the notion that a posture of velum lowering is maintained during the entire nasality spreading span would be incorrect. In order to produce a voiceless oral obstruent stop, the velum must be raised, as schematized in Figure 3. Here two separate lowered velum intervals are interrupted by a raised velum posture for the [t]. This hypothetical outcome will be referred to as transparent segment discontinuity. In this configuration the nasality in [ã] cannot be a direct result of nasality spreading under Strict Segmental Locality, since nasalization has not permeated through the intervening [t]. Articulatory Locality also rules out nasalization spreading leapfrogging [t], because it produces two non-contiguous lowered velum gestures. If the acoustic data for Guaraní nasal harmony support an outcome like that schematized in Figure 3, then it would seem to present a case in which the articulatory property that characterizes a spreading feature does not continue through a transparent segment. Under these circumstances, evaluating the proposals of Strict Segmental Locality and Articulatory Locality will require some additional attention. Whether these could be sustained as universals of locality in phonological feature spreading will hinge on the details of theoretic framework that are assumed, for instance, whether abstract intermediate structures are adopted. This issue is addressed in section 4.

1.2 Nasal harmony in Guaraní

Guaraní belongs to the Tupí family. The Guaraní language is centered in Paraguay, where it is one of the country's two official languages (along with Spanish) and is spoken by over four million people. Guaraní is also spoken in bordering regions of Argentina and

Brazil. A large number of Paraguayan Guaraní speakers (over 50%) also speak Spanish; use of Guaraní predominates in rural areas and in certain sociolinguistic contexts. In order to establish the appropriate set-up for the phonetic investigation, the core properties of Guaraní nasal harmony are briefly outlined.

The surface consonant inventory for Guaraní is given in Table 2 (after Gregores and Suárez 1967). The notation [a/b] indicates two allophones of the same phoneme. Observe that all of the voiced segments have oral and nasal allophones; the oral allophones occur in the onset to an oral vowel and the nasal allophones occur before nasal vowels. Consonants occur only in onsets; the canonical syllable structure of Guaraní is (C)V (Rivas 1975: 135). Voiced stops are produced as prenasal in oral syllables and as nasal stops in nasal syllables. The prepalatal voiced obstruent has variable oral realizations, ranging among [ᵈj], [d͡ʒ], [ʒ], [j]. In nasal syllables, this segment is a full nasal stop. The segments transcribed as [ʋ], [ɰ], and [ɰʷ] are grouped by Rivas (1975) with the sonorants, and they are described by Gregores and Suárez as frictionless spirants (1967: 81-2). In nasal syllables, these segments are produced as nasal approximants. Voiceless segments are described as having voiceless oral allophones in all environments. The velar fricative is in free variation with glottal [h] (Gregores and Suárez 1967: 81). The Guaraní vowels are shown in Figure 4. There are three basic vowel heights and three degrees of tongue advancement. Vowel nasalization is phonemic in stressed syllables only; elsewhere the distinction is allophonic.

Nasal harmony in Guaraní produces cross-segmental spans of nasalization. Nasal spreading in the word is initiated by a nasal vowel in a stressed syllable and is bidirectional. Nasalization spreads to all voiced segments and is reported to not affect voiceless consonants. Spreading is blocked by a stressed syllable containing an oral vowel. In blocking syllables, both the vowel and its onset consonant remain oral. In general, all voiced segments in a syllable in Guaraní agree in orality and nasality; in the case of prenasal segments, it is by virtue of their oral release that they qualify as oral. Nasal spreading triggered by a stressed nasal vowel is illustrated in (3) (nasal harmony spans are underlined). Blocking by a stressed oral syllable is exemplified in (3c-d). (Examples (3a-b) are from Rivas 1975 and (3c-d) from Gregores and Suárez 1967.)

(3)	a.	/^{n}do-ɾoi-^{n}duˈpã-i/	→	[nõɾ̃õĩnũˈpãĩ]
		not + I-you + beat + NEG		‘I don’t beat you’
	b.	/ɾo-^{m}bo-poˈɾã/	→	[ɾ̃õmõpõˈɾ̃ã]
		I-you + CAUS + nice		‘I embellished you’
	c.	/i^{d}jaˌkãɾaˈku/	→	[ĩɲ̃ãˌkãɾ̃ãˈku]
				‘is hot-headed’
	d.	/aˌkãɾaˈɣ^{w}e/	→	[ãˌkãɾ̃ãˈɣ^{w}e]
				‘hair (of the head)’

Words like (3c-d) contain both a nasal harmony span and an oral span. In order to focus on the realization of voiceless stops in nasal spreading domains, the study below will not include words containing both nasal and oral stressed vowels. It is apparent in the above data that nasality spreads across morphemes in a word. In words with prefixes, nasalization in the root spreads to the prefix (see (3a-b)). The situation is somewhat more complicated with suffixes: some are susceptible to nasality spreading and others have a fixed oral or nasal quality (Rivas 1975; see Walker 1998 for a formal account of this kind of suffix behavior in nasal harmony). In order to avoid this complication, the present study examines only words without suffixes. It should be noted that word-medial prenasal stops trigger regressive nasal spreading, but words with this phonological structure were not included in the study.

2. Method

2.1 Stimuli and data collection

In order to compare the acoustic properties of intervocalic voiceless stops in oral versus nasal contexts, this study considers unsuffixed bisyllabic words of the form (C)VˈCV, which follows the most common pattern of Guaraní stress in roots. In some words the initial consonant is a pronominal prefix included in the domain of nasal harmony. The medial consonant in all words was a voiceless stop from the set [p, t, k]. Each bisyllabic word defines a nasal harmony domain, where the nasality of the stressed vowel determines the oral/nasal quality of the word. In nasal words, both vowels are nasal by regressive spreading from the final stressed nasal vowel, and in oral words, both vowels are oral. Six oral/nasal minimal or near-minimal pairs were compared for each of the three places of articulation for voiceless stops, and in the case of [t], there were seven word pairs, giving a total of 38 words. Word pairs matched minimally in the place of the medial stop, in the height of the vowels following the voiceless stop, and in the height of the vowels preceding the voiceless stop. Some examples are given in (4). A complete list of the word pairs used in the study is provided in the appendix.

(4) Examples of Guaraní bisyllabic word pairs

	Nasal: (C)Ṽˈ CṼ	Oral: (C)VˈCV
a.	[põˈpĩ] 'to peel, strip'	[ᵈjoˈpi] 'to itch, sting'
b.	[tãˈtĩ] 'horn'	[taˈti] 'daughter-in-law'
c.	[õˈkẽ] 'door'	[oˈke] 'to sleep'

The subject was a Paraguayan male, 32 years of age, who has spoken Guaraní since before the age of 10 with native proficiency. The context of Guaraní use for the subject is as a spoken language, rarely as a written one. The language was spoken by the subject most frequently in the countryside or marketplace, corresponding to a common sociolinguistic situation of language use in Paraguay. Other languages spoken by the subject are Spanish, Portuguese, and English. At the time the recordings were made, the subject had spent three school years outside of Paraguay (in England and the United States), but he returned to Paraguay for four months of each of those years, during which he would speak Guaraní and Spanish. The written word list was carefully reviewed with the subject in advance of the recording to ensure familiarity with all of the words. With this advance exposure, the written format of the list did not pose a problem, since many of the orthographic conventions of Guaraní follow Spanish ones.

The recordings were made in a sound-insulated room. Words were read in an oral word frame: [eɾe ‘X’ ᵈjeɯ] ‘say ‘X’ again’. In this sentence, the main stress fell on the final vowel of the CVCV word. Words in the carrier sentences were read at a normal speech rate. The 38 words of interest along with 42 filler words were grouped in a list composed of eight random sets of 10 plus an extra word at the beginning and end of each set randomly selected from among the base of 80 words; these first and last tokens were discarded. The filler words were all of the form (C)VˈCV. Within each set no stimuli were repeated, and minimal pairs appeared only in separate groups. Each group of words was titled with a capital letter (A-H) and numbered on the left. They were presented on a total of three pages with blank space visually separating groups. Two word lists were prepared according to this format composed of the same words but presented in a different order. The two lists were read in alternation, one list read a total of four times and the other three times, with the aim of recording at least six valid repetitions of each word. Three breaks in recording were taken, one after the first list was read, and then one after each reading of both lists.

2.2 Data analysis

The recordings were digitized at a sampling rate of 20,000 Hz. Durations of various of the segmental components were measured using Kay Elemetrics Computerized Speech Lab Model 4300, making reference to both waveforms and spectrograms. For each token, four time points were identified (see Figure 5). The first point (a) in Figure 5 is defined by the initiation of closure for the medial voiceless stop. This is signalled by the beginning of a gap in the spectrogram at the end of vowel formant structure for the first vowel and the sudden decline in waveform amplitude. The second point (b) marks the end of voicing during the initial portion of the stop closure, signalled by the end of periodic oscillations in the waveform. The third point (c) marks the release of stop closure, coinciding with the occurrence of a burst spike on the spectrogram and the initiation of aperiodic noise on the waveform. Finally, (d) marks the onset of voicing in the following vowel, indicated on the waveform by the resumption of periodic oscillations after the aperiodic burst energy. On the spectrogram this corresponds to the beginning of a voicing bar and/or vertical striations.

Because of the root-final stress in the bisyllabic words, the amplitude of the second vowel was much greater than the first. In many tokens this made it difficult to identify the initiation of closure in an unmodified spectrogram, because formant structure for the first root vowel was very faint. In order to enhance visibility of the formants in the unstressed vowel, two steps were taken. First, the amplitude of the speech signal was increased by a factor of two from the original to improve the darkness of the displayed image. (The spectrogram displayed in Figure 5 has undergone this double gain). If the increased amplitude was still not sufficient to determine the edges of the first vowel, pre-emphasis was applied to flatten the spectral shape of the signal and increase the relative amplitude of the higher frequencies with respect to those of the lower frequencies. This made visible the areas of the signal where formant energy occurred. Since other properties of the signal, such as voicing, were distorted in the resulting spectrogram, the other points were identified before pre-emphasis was performed. (Pre-emphasis was not performed in the spectrograms shown in this article).

From the four marked points for each token, various durations were calculated. The following report focuses on five of these durations:

(5)
- i. Closure voice duration. The duration from initiation of stop closure (a) (see Figure 5) to the end of voicing during the initial portion of stop closure (b).
- ii Closure duration. The duration from initiation of stop closure (a) to the release of closure (c).
- iii. Closure voiceless duration. The duration from the point of end of voicing during the initial portion of the stop closure (b) to the release of closure (c).

iv. Voice onset time (VOT). The duration from the release of stop closure (c) to the onset of voicing (d).

v. Total voiceless duration. The duration from the end of voicing during the initial portion of the stop closure (b) to the onset of voicing in the following vowel (d).

All of the above except closure duration are measures in which one or both ends of the interval is a voicing-related event. The additional measure of closure duration allows for calculation of the following ratios of the duration of stop closure to the duration of voicing/voicelessness intervals:

(6) i. Closure duration/VOT.

ii. Closure duration/Closure voice duration.

The reason that the above ratios were calculated rather than only evaluating closure duration, VOT, and closure voice duration separately was to control for any word-to-word or token-to-token variation in speaking rate.

The durations and ratios outlined above were used as dependent variables in a two-factor General Linear Model (GLM) Analysis of Variance (ANOVA) model (SuperAnova, Abacus Concepts 1989). The two factors were place of articulation of the medial stops (levels: p, t, k) and nasality (levels: oral, nasal). Probabilities less than or equal to 0.05 were considered significant. A Scheffe's S-test was used post-hoc to test for significant differences within the factor of place of articulation. Three planned comparison of means (contrasts) were used to test for differences among [p]-nasal versus [p]-oral (i.e. [p] in nasal versus oral contexts), [t]-nasal versus [t]–oral, and [k]-nasal versus [k]-oral. In general, data derived from the first six repetitions of a word was used.[2]

3. Results

The results of the study are presented in two segments. First, the general acoustic character of stops in oral and nasal words is discussed, focusing on the question whether voiceless stops are produced as transparent obstruent stops in nasal harmony, i.e. without the acoustic patterns of nasals. Next the effect of nasal contexts on properties of voicing timing in voiceless stops is addressed. This latter segment reports on the details of closure and voicing timing in oral versus nasal words, followed in each case by an examination of the effect of place of articulation on any timing differences. These results relate to the possibility of a nasal leak configuration and the phonetic implementation of the feature [–voice].

3.1 Acoustic patterns

3.1.1 Question 1: Are voiceless stops acoustically transparent?

A striking acoustic feature of the target voiceless stops is that /p, t, k/ are typically realized with the acoustic properties characteristic of oral obstruent stops when they occur in nasal harmony spans. In such contexts, nasality in the flanking vowels was clearly audible. However, it is not the case that voiceless stops in nasal spans display acoustically detectable nasalization. They do not exhibit the characteristics of voiced nasals during the closure nor do they display the acoustic properties of voiceless nasal stops; rather they present an absence of energy consistent with simultaneous oral and nasal occlusion. To illustrate, a representative sample spectrogram and waveform for the nasal word [õˈkẽ] ‘door’ is shown in Figure 6. Comparing this spectrogram to the one of the VCV portion of the oral word [poˈko] in Figure 5, it is apparent that the same acoustic pattern is seen in both stops.

The pattern seen here may be contrasted with that expected for a nasal stop. Voiced nasal stops are characterized acoustically by a periodic waveform and a weak formant structure. The first formant has the highest intensity and is centered at about 250 Hz. Additional formants occur at approximately 2500 Hz and 3000 Hz (Ladefoged 1993). Studies of the acoustic characteristics of voiceless nasals have identified a noise pattern that appears to result from a high volume of airflow (Ladefoged and Maddieson 1996). Turbulence generated at the nostrils produces a low intensity frication during these segments that lacks much distinctive spectral shaping (Ohala and Ohala 1993). The closure phase of the Guaraní stops in question does not register either of these nasal acoustic patterns—a gap is seen during the closure interval in the spectrogram, which is consistent with the character of an oral stop. Further, stops in Guaraní nasal contexts are accompanied by a robust burst, suggesting that a build-up of pressure in the oral cavity has occurred, and hence a significant amount of air has not escaped through the nasal passage during the closure. Also apparent here is the absence of voicing for a substantial period during the stop. This acoustic pattern was found in all of the stops in nasal words. The waveform and spectrographic information is strongly suggestive that nasal airflow does not occur during these stops to any substantial degree. It should be noted that this information cannot conclusively confirm the lack of nasal airflow during these segments. However, since the characteristic acoustic features of nasal stops are wholly absent in these segments, the acoustic evidence nevertheless offers persuasive support for a lack of any audible nasal airflow.

The acoustic information supports the transparency effect for voiceless buccal stops that has been reported in the Guaraní grammars. Voiceless stops in nasal harmony contexts display the acoustic characteristics of an oral obstruent. Hence, the closure of these segments appears to be oral, and they do not correspond to a situation in which the velum remains fully lowered throughout the duration of the stop. This rules out a view of nasality spreading corresponding to that depicted in Figure 1, where full velic opening is sustained through the stop. In other words, the phonetic form of voiceless stops indicates that it is not the case that spreading of a nasal feature or gesture produces wide velic opening in an uninterrupted stream of segments. H1 is untenable under these results. Note, however, that the findings reported thus far leave open the question whether the production of the medial stops is best represented by the schematization in Figure 2 or Figure 3. If the stop matched the schematization in Figure 2, depicting H2, then the velum would remain open only a minimal degree during the stop. This could result in an acoustic pattern much like that of an oral stop, but this nasal leak configuration is expected to be detectable from an increase in the voiced portion of the stop. If, on the other hand, the stop were produced as in Figure 3, corresponding to H3, then the velum would be raised, resulting in a voiceless oral stop. The matter of voicing timing is examined in the next section.

3.1.2 Question 2: Does nasal harmony context affect voicing timing?

Next the question of voicing timing is addressed, focusing on whether nasal harmony contexts produce any difference in this respect in voiceless stops. First, voiceless stops in both oral and nasal environments are observed to share a voicing timing pattern: voicing persists part-way into the stop closure, followed by a period of voicelessness, which begins during the closure and persists for an interval after the release (see Figures 5-6). Although these properties characterize voiceless stops across contexts, some details of the timing differ by environment. Two effects are observed in nasal contexts, and a key aspect of voicing timing remains fixed.

3.2 Quantitative results

3.2.1 Effect 1: Ratio of closure duration to VOT

By way of a general overview of the voicing timing patterns, Figure 7 schematizes the time line of average voicing overall measures for stops in oral and nasal contexts, and Figures 8-10 present time lines for each place of articulation. The specific results are detailed below. First, a context-induced effect identified in this study is that the average ratio of closure duration to VOT, i.e. the average of the closure duration/VOT ratios, is overall significantly smaller in nasal contexts than in oral ones. Table 3 presents the means and standard deviations for each ratio and duration split by the factor of nasality. There is a statistically significant difference in the ratios of closure duration over VOT, taken across all three places of articulation. The average for oral contexts of 7.34 is greater than the nasal average of 5.66 ($F(1, 217)=31.298$, $p<0.0001$). The cause for the smaller closure duration/VOT ratios in nasal words can be traced to both of the logically possible contributors: in nasal contexts VOT is significantly longer and closure duration is significantly shorter. The average VOTs are 26.58 ms in oral words and increase to 32.42 ms in nasal words ($F(1, 217)=26.008$, $p<0.0001$). Mean closure duration for the intervocalic voiceless stops in oral environments is 165.52 ms, which is longer than the nasal average of 158.55 ms ($F(1, 217)=9.243$, $p=0.0027$).

Thus far the results report findings across the entire sample of data. When the tokens are examined according to place of articulation of the stops, it emerges that place interacts for closure duration/VOT in nasal versus oral words ($F(2, 217)=7.522$, $p=0.0007$). Table 4 details the means and standard deviations for ratios and durations split by nasality and place of articulation. For both [p] and [t], a significant contrast was found for the closure duration/VOT ratio in oral contexts versus nasal ones. For [p] the contrast is greatest, with an average value in oral words of 8.88 comparing with an average of 5.86 in nasal words ($F(1, 71)=32.719$, $p<0.0001$). The averages for [t] are roughly similar: oral 8.67 versus nasal 6.84 ($F(1, 83)=14.053$, $p=0.0002$). The velar stop differs: the oral average closure duration/VOT is 4.24 and nasal average is 4.10, a difference that is not statistically significant. A significant difference within the factor of place of articulation was found for [p] versus [k] ($p<0.0001$) and [t] versus [k] ($p<0.0001$), but not for [p] versus [t].

In addition to not having a significant contrast in the closure duration/VOT value in oral versus nasal contexts, [k] is remarkable in two other respects. First, the value of closure duration/VOT for [k] is much smaller than for [p] or [t]. Second, the standard devation for [k] is smaller than for other places of articulation. The standard deviation for [k] is in the neighborhood of 1, but for [p] and [t] the standard deviation is over twice as high. This suggests that aspects of the timing with velars are highly fixed in comparison to the other stops. These points are returned to in the discussion in section 4.

With regard to VOT once again [p] and [t] conform to the general pattern, exhibiting a significant contrast in oral versus nasal contexts. For [p] the oral average VOT is 20.59 ms versus nasal 31.47 ms ($F(1, 71)=28.871$, $p<0.0001$). In the case of [t], the oral average is 20.38 ms versus nasal 26.65 ms ($F(1, 83)=11.193$, $p=0.001$). The velar stop, however, does not display a significantly different VOT in oral and nasal words; its VOT measures consistently about 40 ms. A significant difference within the factor of place of articulation was again found for each of [p] and [t] versus [k] ($p<0.0001$), but not for [p] versus [t]. Notice that the mean VOTs for [k] far exceed those of [p] and [t]. The occurrence of a longer VOT for velars than for labial and coronal stops accords with the findings of other studies on place and VOT; Lisker and Abramson (1964) were the first to report this observation (see also Fischer-Jørgensen 1964; Smith 1978). In the Guaraní data, this effect is such that even in oral contexts, the average VOT for [k] is about 10 ms longer than the VOT for [p, t] in nasal contexts. It should be noted that the standard deviations here are consistently greater in nasal words. This difference is taken up in section 4.

Matching the pattern of the overall measures, a significantly shorter closure duration was found for [p] and [k] in nasal contexts in contrast to their counterparts in oral contexts. For [p] the oral average is 168.86 ms versus 158.64 ms in nasal environments ($F(1, 71)=5.826$, $p=0.0166$). [k] presents a similar asymmetry: oral average 163.17 ms versus nasal 153.47 ms ($F(1, 71)=5.251$, $p=0.0229$). The closure duration for [t] was not significantly shorter in nasal words. Connected to this, in section 3.3 a phenomenon is discussed whereby some tokens of nasal words with [t] presented two burst events, which correlated with an increased closure duration. A post-hoc Scheffe's test revealed no significant differences within the factor of place of articulation for closure duration.

To summarize, the findings reported so far are that the ratio of closure duration to

VOT is greater in oral contexts than in nasal ones. A strong contributing factor is a longer VOT in nasal words, and a somewhat weaker factor is a shorter closure duration in nasal words. The velar stop is somewhat exceptional in not having a significantly different closure duration/VOT average in nasal versus oral words or a significantly different average VOT.

3.2.2. Effect 2: Ratio of closure duration to closure voice duration

The second main effect discovered for voiceless stops in oral versus nasal words is that the average ratio of closure duration to closure voice duration, i.e. the average of the closure duration/closure voice duration ratios, is overall significantly smaller in nasal words. The nasal average is 6.61 versus oral average 8.26 ($F(2, 217)=6.257$, $p=0.0131$). This means that a greater portion of the closure is voiced in a nasal vocalic context. The factors of nasality and place did not present a significant interaction for this variable ($F(2, 217)=1.425$), and a post-hoc Scheffe's test showed no significant differences within the factor of place of articulation.

When examined by place of articulation, it emerges that a contrast in the closure duration/closure voice duration ratios holds specifically of tokens with [t]. The average value for oral tokens is 8.85 and for nasal is 5.98 ($F(1, 83)=7.697$, $p=0.0060$). Statistically significant oral/nasal contrasts were not found within place for [p] or [k]. It should be noted that the standard deviation for [t] is quite high (7.86 for oral tokens, 4.97 for nasal tokens). For reasons that are not well understood, the wide variance arose primarily from productions of the word pair [ᵐboˈtɯ]/[mõˈtĩ], which displayed a standard deviation of 19.05 for oral tokens and 11.98 in nasal tokens (three productions in particular displayed aberrant values for closure duration/closure voice duration). With this word pair excluded from the data, the standard deviation for [t] diminishes to 3.63 oral and 1.38 nasal. In general, oral tokens exhibited a higher standard deviation for the closure duration/closure voice duration ratio than nasal tokens, though the cause for this is unclear.

Although closure duration was found to be shorter in nasal words for [p] and [k] (see section 3.2.1), this was not sufficient to produce a significant contrast in the closure duration/closure voice duration ratio for these stops. Recall, however, that [t] did not have a significantly different average closure duration in oral versus nasal contexts. For [t], a greater closure voice duration in nasal environments yields an increase in the proportion of the voiced interval of the closure. Between oral vowels the average closure voice duration for [t] is 24.78 ms and in nasal words this increases to 34.07 ms ($F(1, 83)=10.993$, $p=0.011$). A significant contrast was not found within [p] and [k] in oral versus nasal contexts for closure voice duration. This result accords with the lack of difference in closure duration/closure voice duration for [p, k]. While [t] displayed longer closure voice durations in nasal contexts, no main effect was found for the factor of nasality with respect to closure voice duration ($F(1, 217)=2.690$).

An effect that is related to the decrease in closure duration/closure voice duration in nasal contexts is a significantly shorter closure voiceless duration in nasal contexts. Between oral vowels, the closure voiceless duration is about 140 ms, while in nasal contexts this falls to about 130 ms ($F(1, 217)=17.655$, $p<0.0001$). The factors of place and nasality did not register a significant interaction for closure voiceless duration $F(2, 217)=0.352$, and a post-hoc Scheffe's test did not show any significant differences within the factor of place of articulation. A contrast within place of articulation for nasal versus oral tokens was found for [t] ($F(1, 83)=8.020$, $p=0.0051$) and [k] ($F(1, 71)=7.762$, $p=0.0058$), but not for [p] ($F(1, 71)=2.871$).

3.2.3 A fixed property: Total voiceless duration

The next finding reported on concerns a fixed property of voiceless stops in oral and nasal contexts. Across the sample of data, it was found that the total duration of voicelessness for stops does not differ significantly in oral versus nasal words, averaging around 165 ms in both contexts ($F(1, 217)=2.841$).

When the means for total voiceless duration are compared by place of articulation, [k] is once again singled out in contrast to the other stops. [p] and [t] conform to the general result, presenting no significant contrast in their total voiceless duration by oral/nasal context. In the case of [k], however, the average total voiceless duration of 180.56 ms in oral words is significantly longer than the average 169.04 ms in nasal ones ($F(1, 71)=6.683$, $p=0.0104$). In addition, the total voiceless duration for [k] exceeds that of [p, t] in oral or nasal environments. With respect to total voiceless duration, [k] is found to be significantly different from [p] ($p<0.0001$) and [t] ($p=0.0002$). However, [p] and [t] are not significantly different from each other for this variable.

To review, we have seen that overall the total voiceless duration is not significantly different in oral versus nasal words, but when we take place of articulation into consideration, it emerges that [k] has a shorter total voiceless duration in nasal words. This is reminiscent of the lack of increased VOT found for [k] in nasal environments, which sets it apart from the other stops, as noted in section 3.2.1.

3.3 Stops with two burst events

Finally, we note a somewhat different pattern that was observed in the release of a small set of voiceless stops in nasal contexts (about 11%). In these divergent productions, the voiceless stops appear to have two events rather than one associated with the burst. The spectrogram in Figure 11, which shows the VCV portion of [hãˈtã] ‘hard,’ illustrates one kind of pattern seen in these exceptional tokens. Here there are two apparently separate burst transients. In tokens like this, the bursts seem to be far enough apart to rule out an occurrence of simply an uneven release that does not produce a burst with a single sharply defined transient (as, for example, was found in some tokens of [k]). In some tokens, a second kind of two-event production was seen in which the second and stronger burst transient was preceded by an interval of energy focused mostly in the higher frequencies.

In both of the two-burst patterns, the second of the burst events displayed the characteristics of the usual release of the stop with the first burst apparently resulting from a brief breach in the oral closure. Tokens exhibiting one of these different spectrographic patterns were restricted primarily to instances of [t] in nasal words. However, the reason for this is not clear. Further instrumental data is needed to understand the articulatory actions involved in producing the first burst event and their correlation with dental stops in nasal vocalic contexts. It should be noted that when the two-burst pattern occurred, the duration from the initiation of closure to the second burst event was often longer than for the regular one-burst-event tokens for [t] (possibly to allow for additional accumulation of intra-oral pressure after the first burst event). Although the two-event pattern occurred in only some of the nasal words with [t] (31%), this increased length raised the average closure duration for [t] in nasal contexts and contributed to [t] being the one place of articulation that did not have a shorter closure duration in nasal words. The mean closure duration for nasal tokens of [t] excluding the 13 tokens produced with two bursts was 159 ms versus the mean of 163 ms across all nasal tokens with [t]. The average closure duration for all oral tokens with [t] was 165 ms. The difference in closure duration for [t] in oral versus nasal contexts with the two-burst tokens excluded was not found to be a significant contrast; however, the F-value increased for this variable ($F(1, 70)=1.586$) from the result across all tokens of [t] ($F(1, 83)=0.219$).

4. Discussion

4.1 Scenario of timing changes in oral versus nasal contexts

We turn now to discussion of the various findings in order to construct an integrated picture of what timing changes take place in voiceless stops between nasal vowels. To begin, the graph in Figure 12 synthesizes the findings concerning total voiceless duration and VOT in oral versus nasal contexts for each place of articulation. Across oral and nasal contexts for [p] and [t], total voiceless duration does not display a significant difference, averaging around 160 ms. However, a change is exhibited in VOT. [p] and [t] display an average VOT of about 20 ms in oral contexts, and in nasal tokens VOT increases to about

25-30 ms. A rather different pattern is seen in the case of the velar stop. The VOT for [k] does not show a significant difference in oral/nasal environments, averaging consistently about 40 ms. Since the VOT for [k] remains essentially constant, the reduced closure voiceless duration found in nasal contexts produces a decrease in total voiceless duration: it falls from an average of about 180 ms in oral contexts to below 170 ms in nasal words.

In interpreting these results, I focus first on the general patterns and then return to the exceptional patterning for [k]. A central finding of this study is that in general the total duration of voicelessness in stops remains fixed across oral and nasal environments, as depicted in Figure 7. However, certain other aspects of closure and voicing timing change in nasal versus oral vocalic contexts. It is hypothesized that in order to maintain a fixed total voiceless duration, the interval of voicelessness undergoes a shift to persist later into the following vowel under circumstances of a shorter closure duration ([p]) or longer closure voice duration ([t])—conditions that were each found to occur in nasal words (see Figures 8-9). In the hypothesized shift, the voiceless interval remains the same in duration, but its timing in relation to onset/offset of stop closure is affected, such that the voiceless portion of the closure is decreased and the VOT is increased. This scenario is supported by the inverse relations that were found between VOT and closure voiceless duration and between VOT and closure duration. Assuming that the data reported from this single speaker of Guaraní are typical of the language as a whole, it is possible that maintaining the same total voiceless duration has a perceptual motivation; a fixed voiceless duration might serve as a significant property for perception of voicelessness in stops, at least in Guaraní.

The shift of the voiceless interval was not found in velar stops (Figure 10). It is suggested that this is related to the fact that velars make the most successful voiceless obstruent stops. In comparison to [p] and [t], the back site of constriction for a velar stop produces a smaller cavity behind the closure, favoring a build-up of pressure which inhibits voicing. The effect of this was seen in the quantitative results, where VOT was found to vary significantly not only with the factor of nasality but also with the factor of place. With regard to the latter factor, [k] was found to have a significantly greater VOT than either [p] or [t]. Recall also that tokens with [k] presented a comparatively low standard deviation in the closure duration/VOT ratio, indicating that aspects of the timing in the production of [k] are considerably more fixed than in [p] or [t]. It is hypothesized that the behavior of [k] in nasal contexts is the consequence of a ceiling effect for the length of its VOT. In nasal environments, the voiceless interval in [p, t] shifts later in relation to closure onset/offset. In the case of [k], a shift does not take place, because its VOT has reached a threshold in its duration in Guaraní, that is, it will not exceed about 40 ms. This means that when the closure duration for [k] is decreased in nasal environments, the voiceless interval does not increase its extension into the following vowel. As a result, the total voiceless duration between oral vowels is greater than that between nasal vowels.

The hypothesized threshold effect in the velar VOT could be understood in one of two ways, which are open to empirical verification in further work. One possibility is that the VOT for [k] is sufficient in length. From this perspective, the duration of post-release voicelessness would be sufficient to cue the voiceless quality of the stop, even under conditions of a shorter closure voiceless duration. Avoidance of further intrusion on the vowel would then prevent the voiceless interval from extending later. The failure of the VOT of [p, t] to meet the sufficiency requirement would explain the shift of the voiceless interval with these stops. A second possibility is that the threshold for [k] is a result of its VOT reaching a maximal length. Under this view, the threshold effect could be a consequence of perceptual factors. It may be that for adequate perceptibility of the stressed nasal vowel, the voiceless portion cannot exceed more than about 40 ms. It is also possible that a maximal threshold for VOT arises simply as an aerodynamic effect, whereby the vocal tract configuration for the vowel plays a role in initiating voicing. The relatively unconstricted airflow during the vowel could produce the necessary drop in transglottal air pressure. It is conceivable that after a duration of 40 ms the aerodynamic properties of the vocalic configuration following a voiceless stop in Guaraní are sufficient to induce voicing.

The 40 ms VOT threshold effect that is hypothesized for Guaraní is supported by data from other languages. In their cross-linguistic study of VOT, Lisker and Abramson (1964) investigate languages that are like Guaraní in presenting a two-category distinction for VOT in stops. Of the four languages on which they report that are generally classified as contrasting voiced and voiceless unaspirated stops (Dutch, Puerto Rican Spanish, Hungarian, Tamil), the voiceless velar stops were found to display an average VOT that was consistently under 40 ms, and voiceless velar stops regularly displayed longer VOTs than voiceless stops with more forward places of articulation. These VOT generalizations were true for both initial stops in a word produced in citation form and stops produced in non-initial position in a sentence. For instance, VOT averages for [k] in Puerto Rican Spanish were 29 ms in initial position and 20 ms for non-initial position within a sentence. These VOT averages are well under the 40 ms average found for [k] in Guaraní, suggesting that the VOT for Guaraní velars is near a maximum for voiceless unaspirated stops.

The outcomes predicted under the hypothesized scenario thus far fit well with the data. In the overall measures, differences in timing are explained as the result of a shift of voicelessness later into the following vowel in nasal words in order to maintain a fixed total voiceless duration. The distinct behavior of [k] in Guaraní is interpreted in connection with the concept of a threshold effect for its VOT. The velar stop follows the general Guaraní pattern of reducing closure duration between nasal vowels. However, since the velar stop does not extend its VOT, we do not find a difference in oral versus nasal words for VOT or the ratio of closure duration/VOT. Also, because the VOT has reached its threshold, [k] fails to preserve a fixed total voiceless duration across oral and nasal words.[3]

A property that thus far stands as only an observed characteristic is the decrease in the voiceless portion of the closure between nasal vowels. When this is achieved by an increase in closure voice duration (in the case of [t]), this may be explained as a post-nasal voicing effect, which has been well-documented in the phonetic literature (for representative examples see Westbury 1983; Westbury and Keating 1986; Ohala and Ohala 1991, 1993; Bell-Berti 1993; Hayes 1995; Pater 1996, 1999; Hayes and Stivers in progress). In fact, the absence of a post-nasal voicing effect in the case of [p] and [k] after a nasal vowel is rather unexpected. In these stops, the decrease in the voiceless portion of the closure is instead produced by a shorter overall closure duration. The occurrence of a shorter closure duration in nasal vocalic environments might be connected to a general finding across languages that nasal vowels are longer than their oral counterparts (see Whalen and Beddor 1989 and citations therein). It is conceivable that a greater length in nasal vowels produces a compensatory reduction in length of the onset consonant in Guaraní in order to maintain a more even syllable duration; adjustments of this kind in consonant and vowel length have been noted in English as part of a general tendency to equalize the length of syllables (as noted by Ladefoged 1993; Laver 1994). In addition the preceding nasal vowel may have a shortening effect on the stop. A study of English by Umeda (1977) reveals that in a word-medial cluster consisting of a nasal stop followed by an oral stop (e.g. [nd], [nt]), the oral stop displays a shorter closure duration than when it appears outside of the cluster. Umeda finds that this shortening effect is unique to nasals. In clusters beginning with [l] or [s], the following consonant tends to be lengthened. It is conceivable that the effect of post-nasal shortening is also induced by nasal vowels. However, to establish whether this is indeed the case would require further study.

The voicing timing results described here raise some directions for future research. It would be productive to replicate the study of timing effects in oral versus nasal words in Guaraní with a larger group of subjects in order to verify that the generalizations hold for a broad base of Guaraní speakers. In other languages with contrasting oral/nasal vocalic environments, it would be interesting to investigate whether a fixed total voiceless duration occurs for voiceless stops. The present findings suggest that a fixed total voiceless duration is a property that contributes to defining voiceless stops. Further work is needed to determine whether this phonetic characteristic is universal or language-particular.

4.2 Theoretical implications

We now turn to examining the theoretical implications of this study. The acoustic analysis of the Guaraní productions has identified certain characteristics of voiceless stops that hold constant across oral and nasal environments.

(7) i. The stops are produced with the acoustic hallmarks of oral obstruent stops.
ii. The stops are voiceless.
iii. The total voiceless duration is fixed in the general case ([p, t]).

Under the assumption that the generalizations found in this study are representative of productions in the language, these results bear on the phonology-phonetics interface in Guaraní. From a theoretical perspective, they have implications both for the issue of locality in phonological feature spreading and for modelling the phonetic implementation of phonological features. The former matter is addressed first in relation to the three hypotheses outlined in section 1.1.

H1 conceptualized nasal feature spreading as producing a strictly continuous span of nasalization, consistent with the proposals of Strict Segmental Locality and Articulatory Locality. This hypothesis posits a [+nasal] feature specification as corresponding to a wide velic aperture in all segments of which it is a property; hence stops in nasal contexts are expected to become audibly nasal. However, as pointed out in section 3.1, the acoustic pattern of voiceless stops between nasal vowels matches that of oral obstruents rather than nasal stops. This indicates that H1 is not supported. The energy that would result from the air flowing through a wide open velum is conspicuously absent. Also, the obstruent-type burst identified in the acoustic pattern signals that a build-up of pressure behind the oral closure has occurred, and hence a significant amount of air has not escaped through the nasal passage. A second alternative consistent with the Strict Segmental Locality and Articulatory Locality views takes the position that realization of the feature [+nasal] in a stop is satisfied if a minimal degree of velic opening is achieved, in particular, the nasal leak configuration where the airflow resulting from the velic opening is sufficient to induce voicing but not audible nasalization. Under H2, a medial voiceless stop with nasal leak is predicted to become voiced in nasal harmony contexts but continue to display the acoustic properties of an obstruent stop. The present study also does not support this scenario. A clear finding is that voiceless stops remain voiceless in nasal harmony spans. There is thus no cue of full closure voicing to indicate a continuous gesture of velic opening at a threshold degree.

H3 posited a phase during the stop during which the velum is fully raised, that is, the transparent segment produces a discontinuity in the spreading lowered velum gesture. This hypothesis is consistent with the acoustic patterning found here: the stop displayed the properties that would be expected in a voiceless plosive produced with a raised velum. It should be noted that the precise timing of velic lowering and raising for H3 is not critical: what is important is that there is evidence that the velum is raised for some portion of the stop in order to interrupt the spreading nasality gesture. The present study thus does not find data to support either Strict Segmental Locality or Articulatory Locality as holding at the level of the phonetic output for transparent voiceless stops in Guaraní nasal harmony. However, these findings leave open the possibility that these conceptions of locality might instead be posited as holding at an abstract phonological level of representation or as a generalization that can be rendered obscure through derivationally opaque rule or constraint interactions. For example, derivational opacity in generative phonology might be invoked such that feature spreading is maintained as strictly local but the application of a later rule causes the spread feature specification to be deleted on the transparent segment, as in the mapping /meta/ → [mẽt̃ã] → [mẽtã]. In this example, nasalization spreads onto [t] but is subsequently deleted, hence obscuring the effect of local spreading (see Vago 1976; Clements 1976; Piggott 1988; Walker 1998 makes a related proposal in Optimality Theory, see Walker 1996 and Ní Chiosáin and Padgett 1997 for analyses calling on a separate level of realizational mapping). Since the indications of the present study are that Strict Segmental Locality and Articulatory Locality do not regularly generalize over all phonetic representations, it would seem that these models of locality do not reduce solely to phonetic principles but rather represent abstract phonological constraints or primitives, albeit ones that arguably have a phonetic grounding. Certain cases of vocalic transparency in vowel harmony might also provide evidence for phonetic discontinuities in feature spreading, but this is subject to further investigation.

Next the implications of this study are considered for modelling the realization of phonological representations. This work has identified a fixed property of total voiceless duration in voiceless stops, though the timing in relation to stop closure/release can be shifted according to oral/nasal context. An implication of this finding is that it confirms the need to identify the principles involved in the phonetic implementation of phonological features (Pierrehumbert 1980; Browman and Goldstein 1986 et seq; Keating 1988, 1990; Cohn 1990, 1993a, b; Huffman 1989, 1993; Kingston 1990; Kingston and Diehl 1994; among others). Various proposals have been made concerning the factors involved in mapping from an abstract phonological representation to a more concrete continuous sequence of timed articulations or gestures, and the voicing timing findings of the present study are briefly considered in relation to two proposals in this area (i) articulatory binding and (ii) the recognition of articulatory and perceptual factors both playing a constraining role.

Some analysts have argued that the phonetic correlates of features are coordinated with other articulations in systematic ways. The binding principle proposed by Kingston (1990) posits a coordination between laryngeal features and stop consonant release. The binding principle is intended to constrain the possible timing of glottal articulations in relation to oral gestures, explaining why laryngeal features more frequently modify aspects of the release rather than the onset of closure. Huffman (1989) makes a related proposal in her investigation of the phonetic implementation of the feature [nasal]. Working in the windows framework of feature realization (Keating 1988, 1990; Cohn 1990), Huffman argues for the existence of articulatory landmarks, which fix the timing of nasality/orality (or other features) in relation to other articulatory events. In the case of oral stops, she finds that the property of orality ([–nasal]) is associated with the point of closure release. Nasal stops on the other hand have the property of nasality ([+nasal]) affiliated with the duration of the closure. The Guaraní data are consistent with these models of feature coordination in that the point of release of voiceless stops in oral and nasal contexts was consistently oral and voiceless.

With regard to voicing timing, recall from section 3.2 that the standard deviations for VOT in nasal tokens were found to be consistently greater than for oral tokens within each place of articulation. If VOT is a function of when the glottis adducts relative to the stop release, then this difference indicates that the coordination of the glottal adduction and oral release is much more variable in nasal tokens. This great a degree of difference in standard deviation cannot be attributed simply to the increase in VOT in nasal words. In addition, the observed difference in standard deviation was specific to VOT; standard deviation for closure duration did not differ systematically for oral versus nasal words within place of articulation. The variability in nasal tokens suggests that in these words the glottal articulation has become ‘unbound’ from the oral articulation in the sense that although voicelessness overlaps closure release, the timing of the boundaries of the voiceless interval do not seem to be strictly anchored in relation to it (John Kingston, personal communication). It is hypothesized that the glottal and oral articulations become unbound as a result of the shift of events in nasal contexts that arises from increased closure voicing or shorter closure duration. Since this explanation attributes the cause of unbinding to a shift in relation to either the onset or release of closure, it suggests that timing of the glottal articulation is connected to both of these events.

An important property of the phonetic implementation of [-voice] found in this study is that total voiceless duration remains fixed and persists longer into the following vowel when the voiceless portion of the closure decreases. Hence it is not the case that the boundaries of the period of voicelessness are fixed in relation to oral gestures, rather there is some range for movement. The need for some flexibility in phonetic implementation is recognized by various researchers (see Lindblom 1990; Kingston and Diehl 1994; Silverman 1995; Byrd 1996a, b; Wright 1996, among others). For example, in their work on the realization of the feature [voice], Kingston and Diehl find that phonetic implementation is governed by certain constraints which limit the range of possible realizations; however, within this range, the speaker may control the outcome, balancing the minimization of articulatory effort with maximization of perceptibility. This notion of a speaker-controlled phonetics provides a good framework in which to characterize the factors involved in the production of Guaraní voiceless stops. Under the assumption that the findings for the subject of this study are generally representative of patterns in the Guaraní language, it is suggested above that a fixed total voiceless duration is maintained in Guaraní to aid perception of voiceless stops. With this understanding, the increased VOT that occurs when the closure voiceless duration decreases can be characterized as a controlled adjustment to accommodate listener-oriented needs. This shift still obeys the coordination constraint of producing voicelessness at the point of release. In the case of [k], the VOT is conjectured to have reached a threshold. This threshold is listener-oriented if the VOT is understood to be sufficient to facilitate perception of the voiceless quality (and indeed, the voiceless quality of the [k] seems to be readily perceptible). If the threshold is instead understood as maximal, with VOT as a consequence of aerodynamic factors, this would be a speaker-oriented effect. In either case, the fixed VOT for [k] is moderated by minimization of articulatory effort.

The Guaraní data supports previous researchers' claims that an acknowledgement of various and sometimes conflicting realizational requirements is necessary in any theory of phonetic implementation. By way of conclusion, we note that future research on this language could prove fruitful if it were to explore a connection between these implementational principles and the transparency of voiceless stops in nasal harmony. As pointed out above, voiceless obstruent stops are not easily accomplished with a lowered velum, indeed the concurrent production of a voiceless plosive with nasalization might be impossible. This antagonism of the featural properties is likely connected to the observed stop transparency. The details of how this antagonism is resolved in relation to continuity in spreading deserves additional investigation. An instrumental study giving more direct information about timing of velic opening and closure (e.g. measuring nasal airflow) in relation to stop closure and release could bring further insight to the locality issue. The results of a nasal airflow investigation of Guaraní would also potentially contribute to identifying the degree to which velum lowering must be maintained in [+nasal] segments and the factors that influence this dimension.

Appendix: Word pairs

/p/

1.	/ɾuˈpa/	[ɾuˈpa]	‘bed’ (1st poss.)
	/nuˈpã/	[nũˈpã]	‘to hit’
2.	/^{d}joˈpi/	[d͡ʒoˈpi]	‘to itch, sting’
	/poˈpĩ/	[põˈpĩ]	‘to peel, strip’
3.	/keˈpe/	[keˈpe]	‘asleep’
	/mboˈpẽ/	[mõˈpẽ]	‘he/she broke’
4.	/peˈpe/	[peˈpe]	‘to flutter, flap wings’ (lit.)
	/^{d}jeˈpẽ/	[ɲẽˈpẽ]	‘to break’
5.	/^{d}jaˈpi/	[d͡ʒaˈpi]	‘to throw, shoot at’
	/^{d}jaˈpĩ/	[ɲãˈpĩ]	‘to cut hair’
6.	/haˈpɯ/	[haˈpɯ]	‘to catch fire’
	/ʃaˈpĩ/	[ʃãˈpĩ]	‘defective, amputated, cut off’

/t/

1.	/kuˈtu/	[kuˈtu]	‘to stick (with), prick, strike’
	/pɯˈtũ/	[pɯ̃ˈtũ]	‘dark’
2.	/iˈta/	[iˈta]	‘stone, rock’
	/ɯˈtã/	[ɯ̃ˈtã]	‘to swim’
3.	/^{m}boˈtɯ/	[^{m}boˈtɯ]	‘to close, shut’
	/^{m}boˈtĩ/	[mõˈtĩ]	‘to cause shame’
4.	/poˈta/	[poˈta]	‘to want, desire’
	/teˈtã/	[tẽˈtã]	‘nation, country’
5.	/taˈti/	[taˈti]	‘daughter-in-law’
	/taˈtĩ/	[tãˈtĩ]	‘horn’
6.	/paˈti/	[paˈti]	‘name of a fish’
	/kaˈtĩ/	[kãˈtĩ]	‘stinking’
7.	/taˈta/	[taˈta]	‘fire’
	/haˈtã/	[hãˈtã]	‘hard’

/k/

1.	/ʃuˈka/	[ʃuˈka]	‘to show’
	/tuˈkã/	[tũˈkã]	‘toucan’
2.	/poˈko/	[poˈko]	‘to touch’
	/moˈkõ/	[mõˈkõ]	‘to swallow’
3.	/oˈke/	[oˈke]	‘to sleep’
	/oˈkẽ/	[õˈkẽ]	‘door’
4.	/heˈko/	[heˈko]	‘custom, behavior’ (3 poss.)
	/hoˈkẽ/	[hõˈkẽ]	‘door’ (3 poss.)
5.	/^{d}joˈka/	[d͡ʒoˈka]	‘to break’
	/moˈkã/	[mõˈkã]	‘to wipe up, wash’
6.	/kaˈka/	[kaˈka]	‘to defecate’
	/haˈkã/	[hãˈkã]	‘branch’

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Endnotes

1 For a study of voiceless fricatives described as transparent in the nasal harmony of Coatzospan Mixtec, see Gerfen (1996). Gerfen's research finds that nasal airflow is maintained during these segments (but see Ohala, Solé and Ying 1998 on the weakening effects of nasal airflow on voiceless fricatives).

2 The following word repetitions were omitted: [djopi] repetition 4, [ɲẽpẽ] repetition 1, [ʃãpĩ] repetition 3, [ɯ̃tã] repetition 2, [tata] repetition 1, and [oke] repetition 1. In these cases, the seventh repetition of the word was substituted, and the six word repetitions actually examined were numbered from 1-6 corresponding to the order in which they were read.

3 Considered from a cross-linguistic perspective, the patterning of [t] with respect to the shift of voicelessness might be expected to fall with [k] rather than with [p] if the threshold effect were one of sufficiency rather than maximality. Maddieson (1984: 34-37) reports that cross-linguistically the bilabial place or articulation is relatively disfavored among voiceless stops. A factor contributing to the dispreference is that the greater size of the cavity behind the closure for bilabials provides conditions for increased transglottal airflow, and hence it is less conducive to a voiceless state (since transglottal airflow favors voicing). The result is that inventories containing just two voiceless stops are most likely to include [t, k] and exclude [p]. While with respect to backness of closure, [t] might be expected to be the next most likely candidate to be excluded from the set of voiceless stops, this is not the case. Maddieson finds that [t] is the most common form of obstruent stop, presumably on the basis of favorable articulatory or acoustic properties correlated with the coronal region of articulation. On the basis of these cross-linguistic tendencies, it might be expected that both [t] and [k] would achieve a voiceless burst threshold, at least in the sense of a sufficient VOT, and only the voiceless period of [p] would undergo a shift in nasal contexts. However, the Guaraní data indicate that this is not the case. [t] patterns with [p], and only the highly robust burst of [k] displays the threshold effect. Thanks to Abby Cohn for raising this issue.

Figures

Figure 1. H1: Continuous wide velum lowering—Full nasalization.

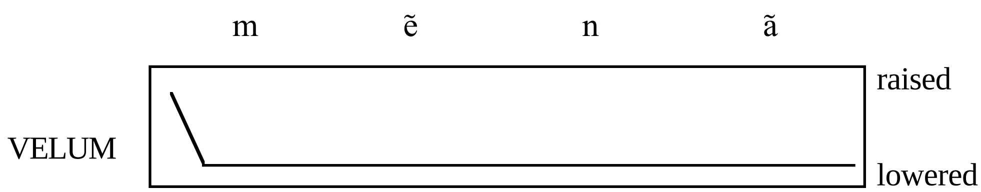


Figure 2. H2: Continuous threshold velic lowering—Nasal leak configuration.

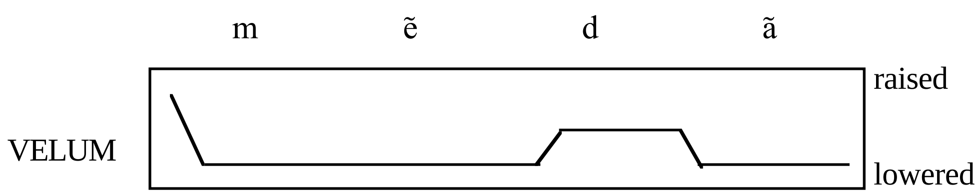


Figure 3. H3: Velum raising during voiceless stop—Transparent segment discontinuity.

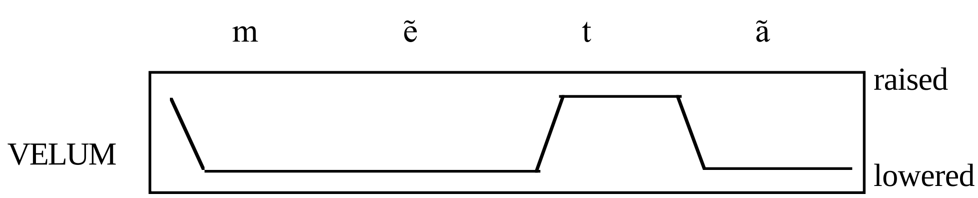


Figure 4. Guaraní vowel inventory.

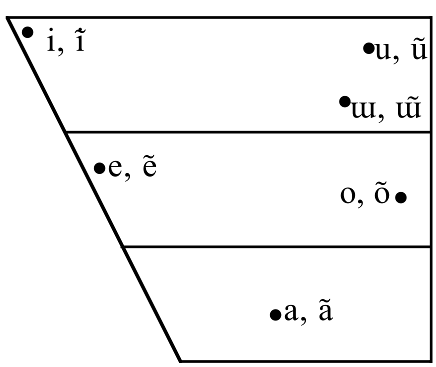


Figure 5. Sample waveform and spectrogram for VCV portion of [po'ko] ‘to touch.’

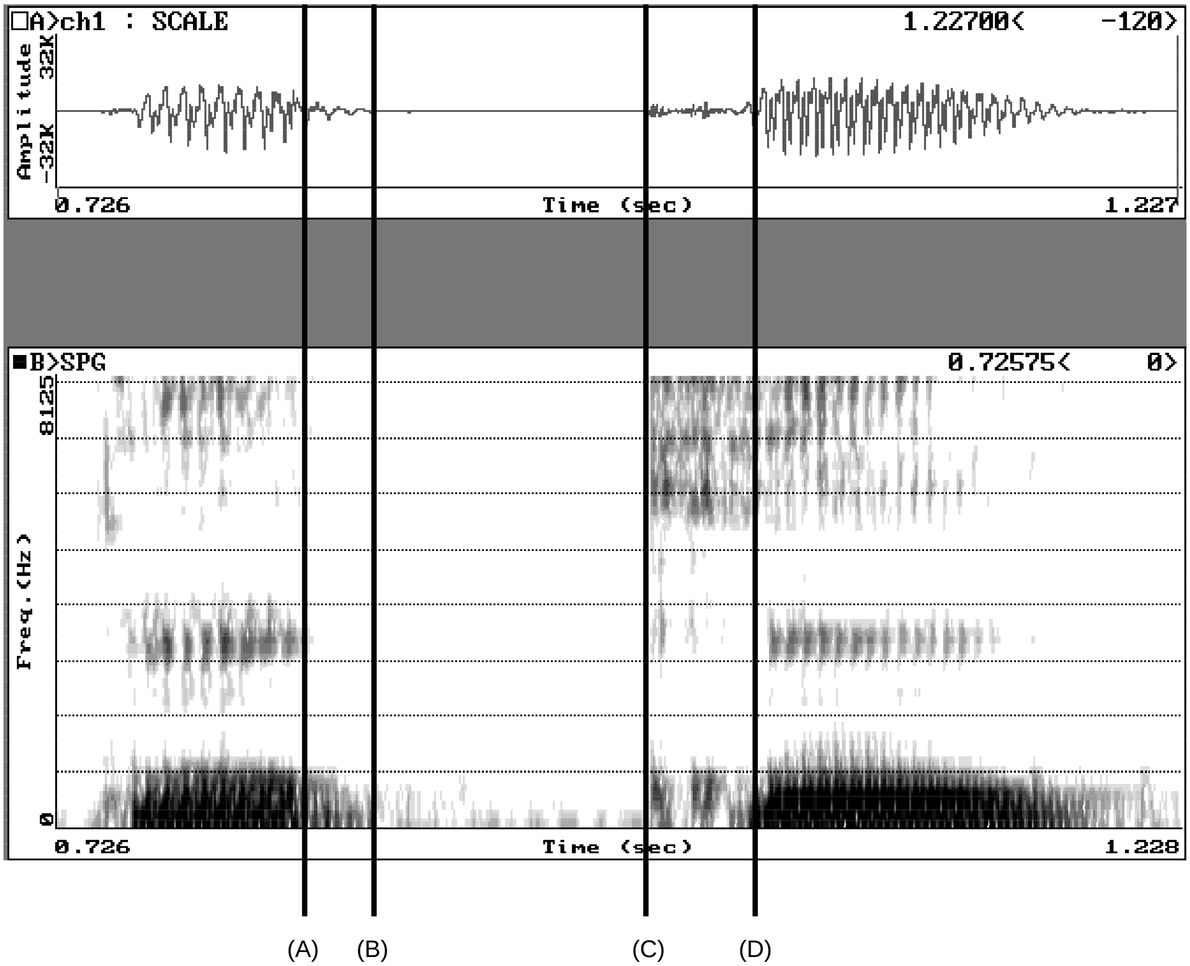


Figure 6. Sample waveform and spectrogram for [õˈkẽ] ‘door.’

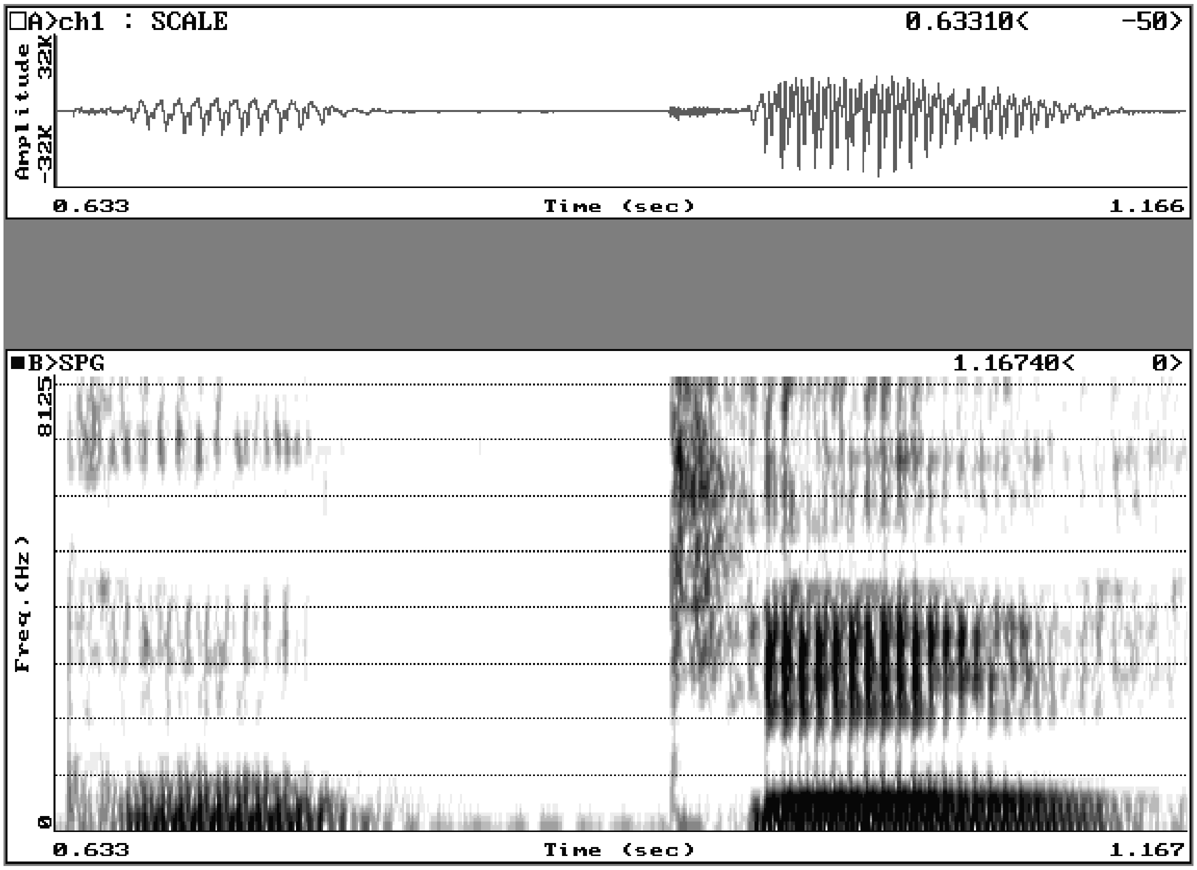
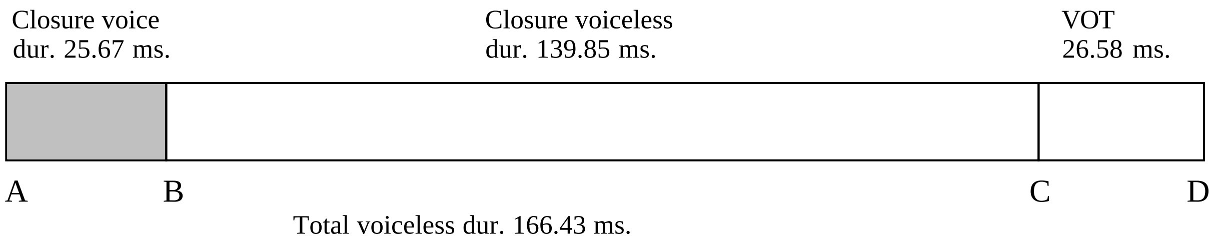
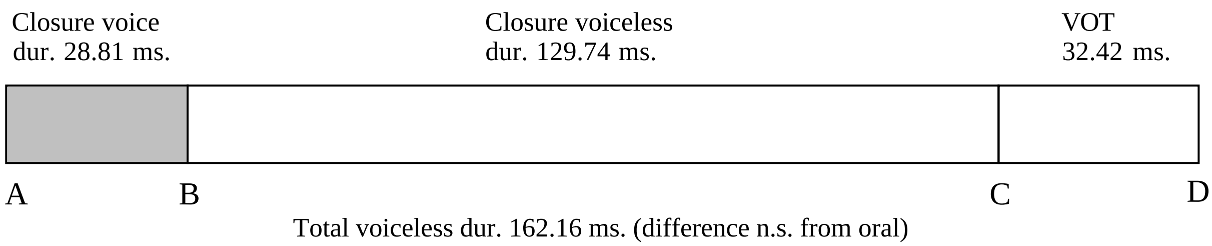


Figure 7. Voicing timing overall measures.

Oral.



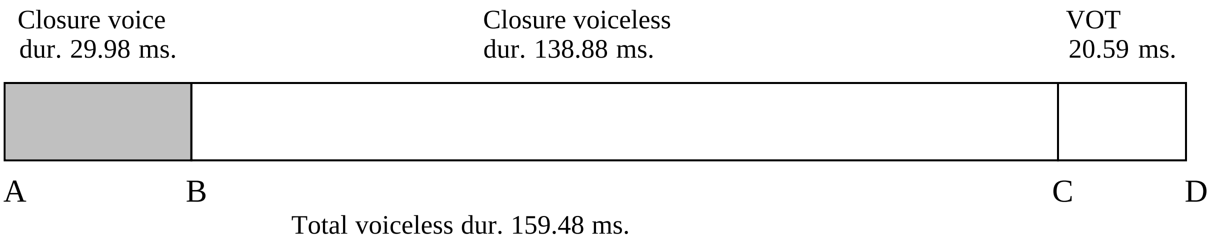
Nasal.



(A) Initiation of closure, (B) Offset of closure voicing, (C) Release of stop closure, (D) Onset of vocalic voicing.

Figure 8. [p] voicing timing measures.

Oral.



Nasal.

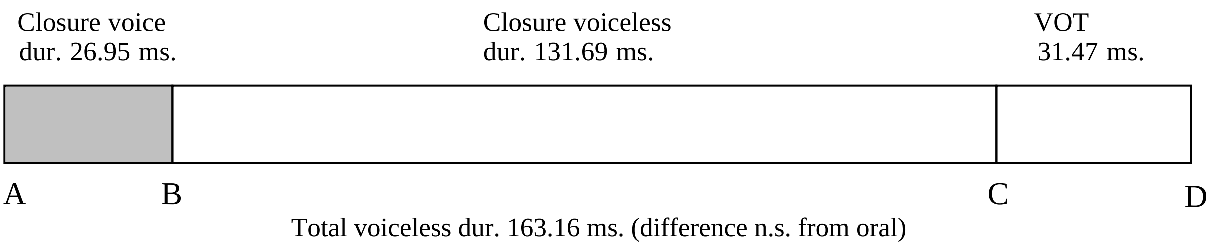
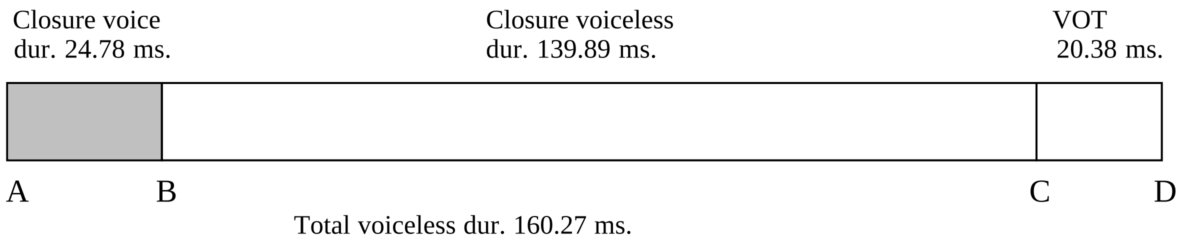


Figure 9. [t] voicing timing measures.

Oral.



Nasal.

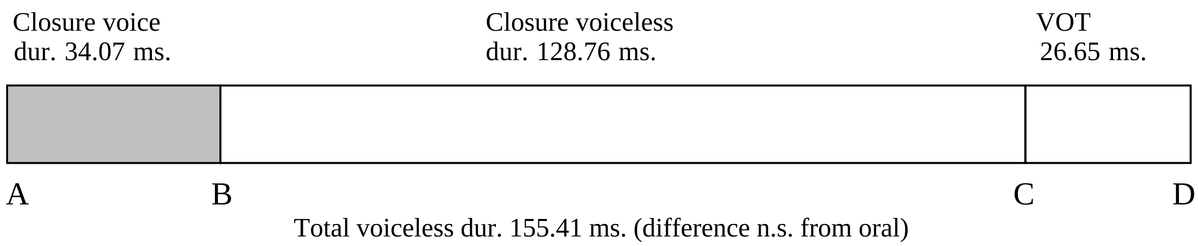
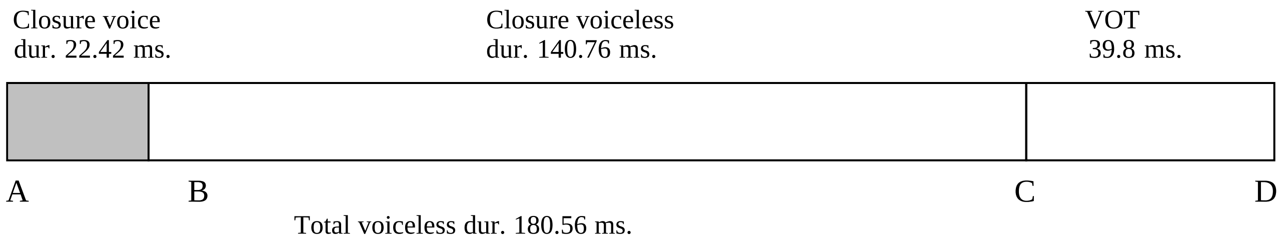


Figure 10. [k] voicing timing measures.

Oral.



Nasal.

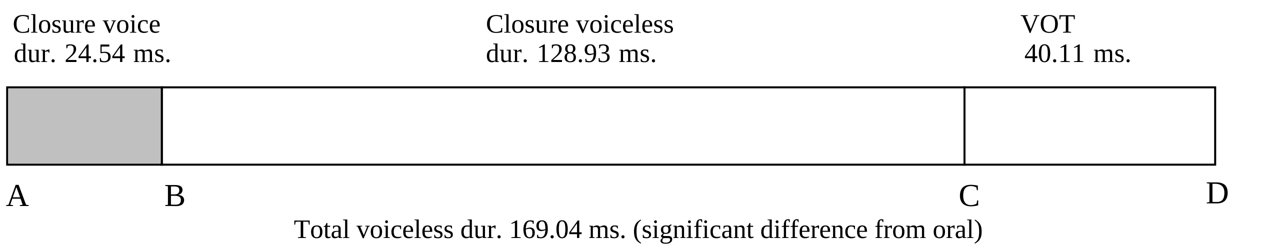


Figure 11. VCV portion of [hãˈtã] ‘hard.’

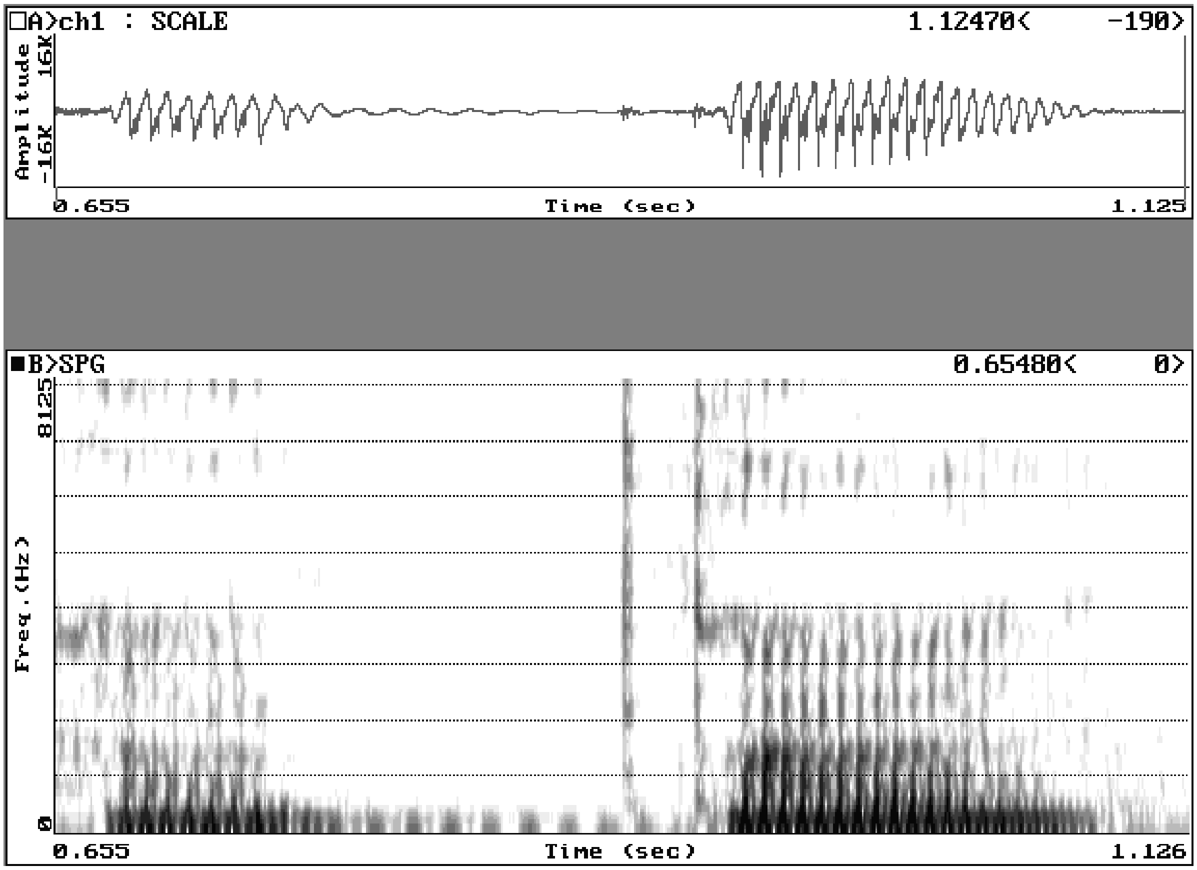
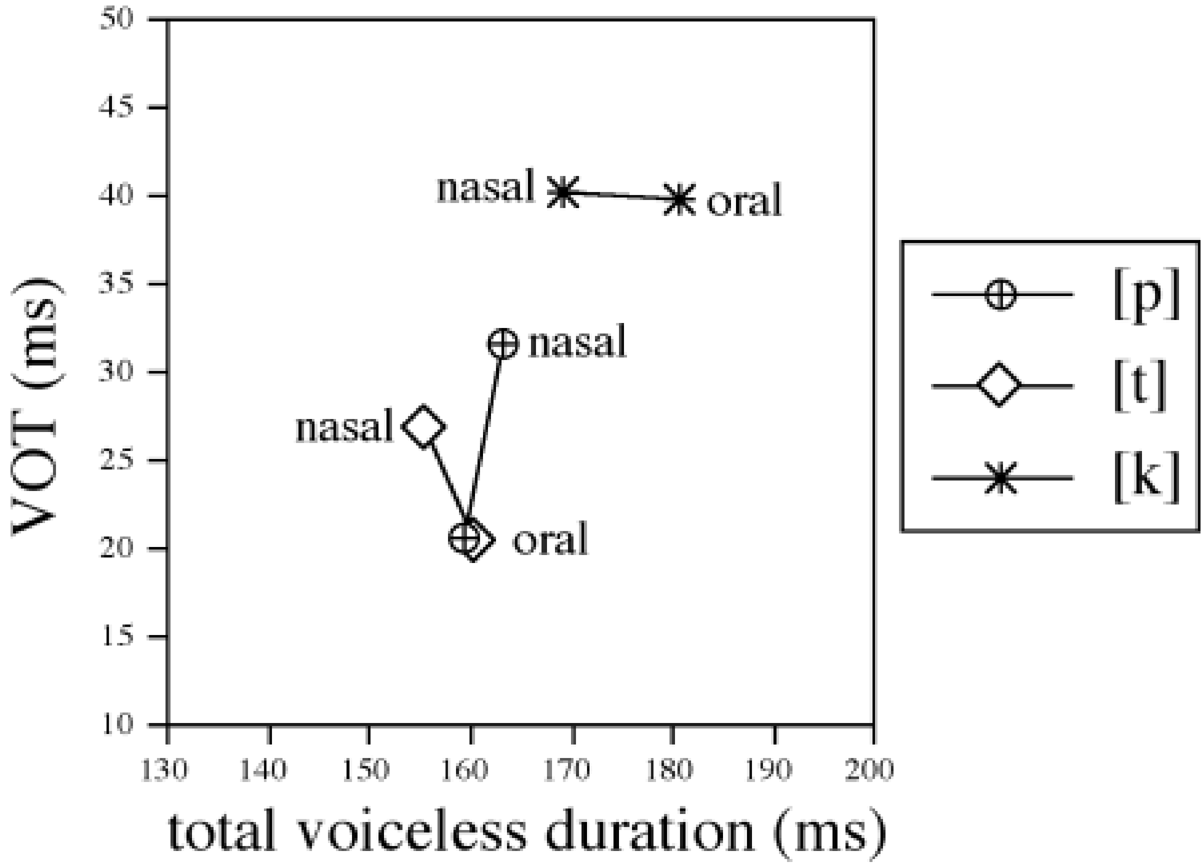


Figure 12. Average Total Voiceless Duration plotted against average VOT for [p, t, k].



Tables

Table 1. Observed possible patterning of segments in nasal harmony.

	Vocoids	Liquids	Obstruents	
Blockers	✓	✓	✓	
Targets	✓	✓	✓	✗
Transparent segments	✗	✗	✗	✓

Table 2. Guaraní consonant inventory:

	Bilabial	Labio-dental	Dental	Alveolar	Pre-palatal	Velar	Labial-Velar	Glottal
Plosive/Nasal	p ^{m}b/m		t ^{n}d/n			k ^{ŋ}g/ŋ	k^{w} ^{ŋ}g^{w}/ŋ^{w}	ʔ
Affricate/Nasal					^{d}j/ɲ			
Flap				ɾ/ɾ̃				
Fricative			s		ʃ	x/h		
Approximant		ʋ/ʋ̃				ɰ/ɰ̃	ɰ^{w}/ɰ̃^{w}	
Lateral Approximant			l/l̃					

Table 3. Means table (ms), split by nasality.

	Mean	Std. Dev.
closdur/VOT, Total	6.50103	2.91037
closdur/VOT, Oral	7.33772	3.08542
closdur/VOT, Nasal	5.66434	2.46641
VOT, Total	29.5	11.72
VOT, Oral	26.58	11.01
VOT, Nasal	32.42	11.74
closure duration, Total	162.04	18.52
closure duration, Oral	165.52	19.19
closure duration, Nasal	158.55	17.20
closdur/closvoice, Total	7.43438	4.9241
closdur/closvoice, Oral	8.25542	5.71821
closdur/closvoice, Nasal	6.61334	3.82753
closure voice dur, Total	27.24	13.42
closure voice dur, Oral	25.67	12.55
closure voice dur, Nasal	28.81	14.12
closure voiceless dur, Total	134.79	19.18
closure voiceless dur, Oral	139.85	19.03
closure voiceless dur, Nasal	129.74	18.04
tot voiceless dur, Total	164.29	21.29
tot voiceless dur, Oral	166.43	22.59
tot voiceless dur, Nasal	162.16	19.77

Table 4. Means table (ms), split by place and nasality.

	Mean	Std. Dev.
closdur/VOT, Total	6.50103	2.91037
closdur/VOT, p, Oral	8.8795	2.67792
closdur/VOT, p, Nasal	5.85892	2.63621
closdur/VOT, t, Oral	8.67034	2.65543
closdur/VOT, t, Nasal	6.8376	2.46489
closdur/VOT, k, Oral	4.24121	0.93045
closdur/VOT, k, Nasal	4.10094	1.16975
VOT, Total	29.5	11.72
VOT, p, Oral	20.59	5.98
VOT, p, Nasal	31.47	11.67
VOT, t, Oral	20.38	5.35
VOT, t, Nasal	26.65	8.72
VOT, k, Oral	39.8	7.69
VOT, k, Nasal	40.11	10.85
closure duration, Total	162.04	18.52
closure duration, p, Oral	168.86	16.96
closure duration, p, Nasal	158.64	15.77
closure duration, t, Oral	164.67	16.49
closure duration, t, Nasal	162.83	19.25
closure duration, k, Oral	163.17	23.76
closure duration, k, Nasal	153.47	14.98
closdur/closvoice, Total	7.43438	4.9241
closdur/closvoice, p, Oral	6.98952	3.34819
closdur/closvoice, p, Nasal	6.68609	2.66644
closdur/closvoice, t, Oral	8.84601	7.86402
closdur/closvoice, t, Nasal	5.97756	4.97267
closdur/closvoice, k, Oral	8.83229	4.41631
closdur/closvoice, k, Nasal	7.28232	3.20489
closure voice dur, Total	27.24	13.42
closure voice dur, p, Oral	29.98	15.44
closure voice dur, p, Nasal	26.95	9.59
closure voice dur, t, Oral	24.78	11.01
closure voice dur, t, Nasal	34.07	18.62
closure voice dur, k, Oral	22.42	9.84
closure voice dur, k, Nasal	24.54	9.48
closure voiceless dur, Total	134.79	19.18
closure voiceless dur, p, Oral	138.88	19.93
closure voiceless dur, p, Nasal	131.69	16.46
closure voiceless dur, t, Oral	139.89	16.37
closure voiceless dur, t, Nasal	128.76	22.6
closure voiceless dur, k, Oral	140.76	21.36
closure voiceless dur, k, Nasal	128.93	13.25
tot voiceless dur, Total	164.29	21.29
tot voiceless dur, p, Oral	159.48	21.98
tot voiceless dur, p, Nasal	163.16	16.16
tot voiceless dur, t, Oral	160.27	16.12
tot voiceless dur, t, Nasal	155.41	23.52
tot voiceless dur, k, Oral	180.56	23.66
tot voiceless dur, k, Nasal	169.04	15.74