# Chapter 4

## A PHONETIC STUDY OF GUARANÍ

In this chapter I report on an acoustic study of intervocalic voiceless stops in oral versus nasal contexts in Guaraní. Guaraní is a language well-known for its nasal harmony, in which all voiced segments become nasalized and voiceless segments behave transparent. 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. In the previous chapter I proposed an analysis of transparency as an opacity effect, producing surface orality of transparent segments in nasal harmony. The findings of the study of Guaraní confirm the need for this result by showing that voiceless stops do typically surface as oral obstruent stops in nasal spreading domains.

In addition to establishing the basic transparent character of voiceless stops in Guaraní, the study makes several findings concerning context-dependent differences in voice onset time, closure voicing, and closure duration in oral versus nasal environments. Although it is apparent that voiceless stops in nasal spans should be represented as phonologically oral, the study identifies some systematic phonetic effects of nasal contexts on voiceless stops. Another discovery is that the total period of voicelessness appears to be fixed independent of context. The period of voicelessness emerges as a feature that is preserved in its total duration but is shifted in relation to stop closure and release in nasal environments. This suggests that, at least in Guaraní, the total voiceless duration is a quality contributing to the definition of voiceless stops. These results thus have implications for the phonetic correspondents of phonological features. An additional interesting set of findings concern the different patterning of the velar stop /k/ in contrast to the anterior stops, /p/ and /t/. The velar stop fails to conform to some of the generalizations established for the other places of articulation. I hypothesize that this separate behavior of /k/ is a consequence of a threshold effect in which the velar stop reaches either a sufficient or maximal limit in its voice onset time, preventing a rightward shift of the voiceless period with just these segments.

This chapter is organized as follows. In section 4.1, I give background on the pattern of nasal harmony in Guaraní. Section 4.2 outlines the set-up of the acoustic study, describing how the data was collected and the method of instrumental analysis. In section 4.3 I report on the results of the study, first highlighting the general patterns, then detailing differences in timing in oral versus nasal contexts, and finally addressing the fixed quality of the total voiceless period. Section 4.4 discusses the implications of these results and provides a schematic scenario of what changes take place in oral versus nasal contexts. Section 4.5 briefly outlines a two-burst phenomenon observed in a small set of tokens, which appears to be correlated to nasal contexts. 4.6 is an appendix presenting the word pairs used in the study.



### 4.1 Nasal harmony in Guaraní

Guaraní belongs to the Tupí family of South America. The Tupí family is geographically located at points along the Amazon River and tributaries, in Paraguay, regions of Bolivia and Brazil, Northern areas of Peru and Argentina, and the South of French Guiana. 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 approximately two 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. There are several grammars and dictionaries of Guaraní (e.g. Guasch 1948, 1956; Osuna 1952; Gregores and Suárez 1967), but little instrumental phonetic study of the language has been documented.[1]

Nasal harmony in Guaraní has excited much discussion amongst phonologists and phoneticians alike (see Gregores and Suárez 1967; Leben 1973; Lunt 1973; Rivas 1974, 1975; Anderson 1976; Goldsmith 1976; Sportiche 1977; Vergnaud and Halle 1978; Hart 1981; van der Hulst & Smith 1982; Poser 1982; Bivin 1986; Piggott 1992; Cohn 1993a; Trigo 1993; Flemming 1993; Steriade 1993d; Penner 1994; Ladefoged & Maddieson 1996; Piggott and Humbert 1997; Beckman 1998; among others). Various aspects of the pattern of nasal harmony are of theoretical interest. These include the transparency of voiceless segments, the nasal allophones of voiced segments, the interaction with metrical structure, effects of spreading across morphemes, and the role of prenasalized segments. The present study focuses on the first point: the transparency of voiceless segments in nasal harmony. I will outline the other main points to establish the appropriate set-up for the phonetic investigation. The following description draws on Gregores and Suárez (1967) and Rivas (1974, 1975).

The surface consonant inventory for Guaraní is given in (1) (after Rivas 1975: 134). The representation [a/b] indicates two allophones of the same phoneme.

[1] Another Tupí-Guaraní language, Guarayu, has had some acoustic investigation by Crowhurst (1998).

(1) Guaraní surface consonant inventory:

| | Labial | Dental | Alveolar | Velar | Labiovelar | Glottal |
|---|---|---|---|---|---|---|
| vcls. stops | p | t | | k | $k^{w}$ | ʔ |
| vcd. stop/affs. | $^{m}$b/m | $^{n}$d/n | $^{d}$j/ɲ | $^{ŋ}$g/ŋ | $^{ŋ}$g$^{w}$/ŋw | |
| fricatives | | s | ʃ | x/h | | |
| sonorants | v/ṽ | l/l̃ | r/r̃ | ɣ/ɣ̃ | $ɣ^{w}$/$ɣ̃^{w}$ | |

A few notes on these segments are in order. First, all the voiced segments have oral and nasal allophones, the oral allophones occurring in the onset to an oral vowel and the nasal allophones occurring before nasal vowels — consonants occur only in onsets, the basic syllable structure is open, (C)V (Rivas 1975: 135).[2] Voiced stops are realized as prenasalized in oral syllables and as fully nasal stops in nasal syllables. The alveolar voiced obstruent has variable oral realizations, ranging among [$^{d}$j], [d͡ʒ], [ʒ], [j], with the prestopped forms occurring in stressed syllables and fully continuant variants occurring elsewhere. In nasal syllables, this segment is a full nasal stop, which sounds like it is articulated in the prepalatal or palatal region. The segments transcribed as [v], [ɣ], and [$ɣ^{w}$] are grouped by Rivas 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. The segment transcribed as [r] represents a voiced alveolar flap. Voiceless segments are reported to have voiceless oral allophones in all environments. The velar fricative is in free variation with the glottal [h] (Gregores and Suárez 1967: 81).

The Guaraní vowels are listed in (2) (Rivas 1975: 134). There are three vowel heights and three degrees of tongue advancement. Nasalization is phonemic in vowels in stressed syllables only; elsewhere the distinction is allophonic.

(2) Vowel inventory:

| | Front | Central | Back |
|---|---|---|---|
| high | i ĩ | ɨ ɨ̃ | u ũ |
| mid | e ẽ | | o õ |
| low | | a ã | |

2 Rivas notes three exceptions to the open syllable generalization. All three cases involve a coda nasal preceding a voiceless stop. Rivas points out that each of these words are interjections and can thereby be exceptional with regard to canonical structure (1975: 135).



Nasal harmony in Guaraní produces cross-segmental spans of nasalization in words. Bidirectional nasal spreading in the word is initiated by a nasal vowel in a stressed syllable. Nasalization spreads to all voiced segments and is reported to skip voiceless consonants. Spreading is blocked by a stressed syllable containing an oral vowel. In blocking syllables, both the vowel and onset consonant remain oral. In general, all segments in a syllable in Guaraní agree in orality and nasality; in the case of prenasal segments, it is by their oral release that they qualify as oral. Nasal spreading triggered by a stressed nasal vowel is illustrated in (3) (nasal spans are underlined). Blocking by a stressed oral syllable is shown in examples (c) and (d). (Below G & S 1967 refers to Gregores and Suárez 1967.)

(3) a. /$^{n}$do + roi + $^{n}$dupã́ + i/ → [nõr̃õĩnũpã́ĩ] (Rivas 1975)
not + I-you + beat + NEG 'I don't beat you'

b. /ro + $^{m}$bo + porã́/ → [r̃õmõpõr̃ã́] (Rivas 1975)
I-you + CAUS + nice 'I embellished you'

c. /i$^{d}$jakã̀rakú/ → [ʔĩɲãkã̀r̃ãkú] (G & S 1967)
'is hot-headed'

d. /akã̀raɣ$^{w}$é/ → [ʔãkã̀r̃ãɣ$^{w}$é] (G & S 1967)
'hair (of the head)'

Nasal spreading is also triggered by the nasal closure of a prenasalized stop. In this case, as would be expected, spreading is always regressive.

(4) a. /ro + $^{m}$bo + he$^{n}$dú/ → [r̃õmõh̃ẽ$^{n}$dú] (Rivas 1975)
I-you + CAUS + hear 'I made you hear'

b. /ro + $^{m}$bo + ɣ$^{w}$atá/ → [r̃õ$^{m}$boɣ$^{w}$atá] (Rivas 1975)
I-you + CAUS + walk 'I made you walk'

In words with prefixes, nasalization in the root spreads to the prefix (see examples above). The situation is somewhat more complicated with suffixes. In general, suffixes can be grouped into two classes, resembling those in Tuyuca discussed in chapter 3. One suffix class is characterized by undergoing spreading of nasalization from the root. Suffixes in the other class are characterized by having a fixed oral or nasal quality.

Alternating suffixes are unstressed in all but two cases;[3] fixed oral suffixes are always stressed and fixed nasal suffixes may be stressed or unstressed. Fixed suffixes do not usually affect the oral/nasal quality of the root. However, if the suffix contains an oral stressed vowel and there is a voiced stop between the stressed suffix vowel and a stressed nasal vowel in the root, then nasalization spreads only as far as the voiced (prenasalized) stop. This produces a root with a nasal span followed by an oral span induced by the oral suffix (Rivas 1975: 138). The pattern is illustrated below with the fixed oral suffix, [ré] 'past'. In (a), this suffix remains oral after a nasal stem. In (b), it produces orality on the final syllable of an otherwise nasal root:

| | | | | | |
|---|---|---|---|---|---|
| (5) | a. | /irũ̀ + ré/<br>friend + PAST | → | [ĩr̃ũ̀ré]<br>'ex-friend' | (Rivas 1975) |
| | b. | / ᵐbẽ̀ⁿda + ré/<br>marry + PAST | → | [mẽ̀ⁿdaré]<br>'widow(er)' | (Rivas 1975) |
| | cf. | / ᵐbẽ́ⁿda/ | → | [mẽ́nã]<br>'husband' | (G & S 1967)[4] |

The purpose of this summary of the data is primarily to review the facts in order to avoid any complications in the nasalization patterns in forms used in the study. The complexities of Guaraní nasal harmony are also fascinating from an analytical perspective, but that is not the main focus of the present chapter. The central analytical feature of Guaraní that concerns us here is that voiceless consonants behave transparent to nasal spreading. Following the analysis proposed for this kind of transparency in Tuyuca in the previous chapter, Guaraní is a language with an opacity effect whereby the nasal spreading constraint has an opaque interaction with the constraints prohibiting voiceless nasal obstruents. This is captured by the ranking in (6) (after the analysis of Tuyuca). For the moment I focus only on the implications of this ranking for voiceless obstruents and will return to the matter of voiced stops presently.

[3] The two alternating stressed affixes are the derivational suffixes: [-ʔó/-ʔṍ] and [-sé/-sẽ́] (Gregores and Suárez 1967: 103).

[4] Rivas also identifies a different kind of suffix behavior exhibited by a 'special class' of suffixes (1975: 138). Suffixes belonging to this class contain an oral stressed vowel and begin with either a voiceless stop or a voiced sonorant of the group [v, ɣ, ɣʷ]. After a nasal root, the suffix-initial consonant is changed to a homorganic voiced prenasalized stop and the suffix vowel remains oral. For some suffixes in this group the change is obligatory and for others it is optional.



(6) Voiceless consonants are transparent to nasal harmony:

P1: *NASOBS >> IDENT-❁O[±voice] >> IDENT-❁O[+nasal]

P2: SPREAD([+nasal], M) >> NASLIQUID >> *NASGLIDE >> *NASVOWEL

Because the nasal spreading constraint outranks all P2 nasalization constraints, this ranking selects a sympathetic candidate in which nasalization spreads to all segments in a nasal morpheme. The P1 nasalization constraint then rules out any candidates containing nasalized obstruents, and IDENT-❁O[±voice] >> IDENT-❁O[+nasal] selects the candidate with nasalization of all voiced segments. This analysis yields an output with surface-oral voiceless consonants in nasal harmony spans. The acoustic study of Guaraní voiceless stops in oral versus nasal contexts is aimed in part at verifying the oral output for 'transparent' segments.

Before proceeding to outlining the details of the set-up of the phonetic study, I will briefly review the analytical implications of some of the other aspects of Guaraní nasal harmony. First, Guaraní nasalization is sensitive to stress. This has led some analysts to posit nasalization as limited by metrical domains (see, e.g., Flemming 1993) or to utilize feature percolation through a metrical tree (Sportiche 1977; Vergnaud and Halle 1978). Beckman (1998) takes a somewhat different perspective, suggesting that faithfulness constraints may be sensitive to prosodically prominent positions. She proposes that one such constraint, IDENT-σ́[nasal], which enforces nasal feature identity in stressed syllables, can derive the effect of foot-bounded nasal harmony in Guaraní. In combination with featural markedness constraints, she shows that faith to stressed positions is also capable of deriving the limitation of phonemic nasality to stressed vowels. Beckman (1998) lays out this analysis with clarity, and the reader is referred to that work for the details.

On the subject of syllable patterns with voiced stops, Beckman (1998) also develops an insightful analysis, drawing on the aperture-theoretic representations of segments proposed by Steriade (1993a, d, 1994). These structures distinguish the closure and release phase of a stop, enabling prenasalized stops to be represented as nasalized during the closure but not the release, as suggested by Steriade (1993a, d, 1994). Making use of a constraint requiring agreement for nasality between adjacent positions of identical degree of aperture (e.g. stop release and a following vowel) and a VOINAS constraint, demanding that the closure phase of a voiced stop be nasal, Beckman is able to explain the syllable nasalization patterns for voiced stops in Guaraní. For the details of this account, the reader is again referred to Beckman's work.[5]

The core analysis of nasal spreading to voiced stops in Guaraní will parallel that of the Tucanoan family. In Guaraní, voiced stops undergo nasal spreading when the following vowel is nasal or becomes nasal through nasal spreading. This is realized with the same kind of ranking as that required for morpheme-internal spreading in Tuyuca outlined in chapter 3 (and repeated in (6) in this chapter). Constraints banning nasalized voiced obstruent stops are located in the P1 segment along with ones against voiceless obstruent stops. IDENT-❁O[±voice] is not violated by a nasal realization for voiced stops, so IDENT-❁O[+nasal] maps voiced stops to fully nasal sonorant stops. Guaraní also resembles the Tucanoan family in having a set of suffixes fixed in their nasality specification. This can be handled under the kind of analysis outlined in chapter 3, with a faith constraint for the class of fixed affixes outranking the constraint driving nasal spreading in the word.

This concludes the overview of Guaraní nasal harmony and its analytical implications. With the pattern of Guaraní nasalization in mind, I turn in the next section to outlining the set-up of the acoustic study of transparent voiceless stops.

## 4.2 Set-up

### 4.2.1 Data and data collection

The goal of the present study is to compare the acoustic properties of intervocalic voiceless stops in oral versus nasal contexts.[6] The data for this study consist of

5 It should be noted that the cross-linguistic behavior of prenasalized stops in nasal harmony still needs further study. Steriade's aperture-theoretic representations have brought new insight into this area. Importantly, since Steriade's representations posit a closure phase for prenasalized stops which is actually specified as [+nasal], they correctly predict that prenasalized stops will trigger regressive spreading in Guaraní. A similar pattern occurs in Tinrin, a Melanesian languge, where regressive nasal spreading is triggered by prenasalized stops along with nasal stops and vowels (Osumi 1995). Yet in some languages it is less clear that prenasalized stops are actually specified for [+nasal] in any portion of the segment. In several of the Tucanoan languages, voiced stops are realized as prenasalized (under certain conditions) in oral morphemes, and they do not trigger nasal spreading. This suggests that prenasalization in the Tucanoan family can occur as a phonetic enhancement effect to favor voicing in stops (Iverson and Salmons 1996 also propose this for some Mixtecan languages). These differences suggest that segments which have been described phonetically as prenasalized stops in various languages may correspond to more than one phonological representation, some having a [+nasal] specification and others not (see Iverson and Salmons 1996 for a similar conclusion). Further pursuit of these issues is left for future research.

6 The present study focuses on voiceless stops only. Voiceless fricatives in Guaraní are also reported to be transparent to nasal harmony, but because of their continuancy, the investigation of these segments requires rather different points of comparison. See Gerfen (1996) for a recent nasal airflow study of transparent and blocking voiceless fricatives in the nasal harmony of Coatzospan Mixtec. Gerfen's study finds that nasal airflow is maintained during a 'transparent' voiceless fricative (but see Ohala, Solé, and Ying 1998 for discussion of the weakening effects of nasal airflow on voiceless



unsuffixed bisyllabic words of the form (C)VCV́, 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, [p], [t], or [k], which formed the subject of investigation. 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 near minimal pairs were compared for each of the three places of articulation for voiceless stops; in the case of [t], there were seven word pairs. 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 (7). A complete list of the word pairs used in the study is given in the appendix of this chapter (section 4.6).

(7) Examples of Guaraní bisyllabic word pairs:

| | Nasal | | Oral | |
|---|---|---|---|---|
| | (C)ṼCṼ́ | | (C)VCV́ | |
| a. | [põpĩ́] | 'to peel, strip' | [ᵈjopí] | 'to itch' |
| b. | [tãtĩ́] | 'horn' | [tatí] | 'daughter-in-law' |
| c. | [õkẽ́] | 'door' | [oké] | 'to sleep' |

The language consultant for the study was a Paraguayan male, 32 years of age, who has spoken Guaraní since before the age of 10. The consultant's proficiency in the language includes both native fluency and native accent ability. The context of use for this speaker is as a spoken language, rarely as a written one. The language was spoken by the consultant most frequently in the countryside or marketplace, corresponding to a common sociolinguistic situation of language use in Paraguay. Other languages spoken by the consultant are Spanish, Portuguese, and English. At the time the recordings were made, the consultant 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

fricatives). In an acoustic study, fricative nasalization could perhaps be judged by comparing amplitude of the fricative energy — this might be stronger or focused at different frequencies if there were nasal airflow — however, a more direct technique, such as direct examination of the velum position, would give firmer results.

reviewed with the consultant 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 with the speaker reading into a microphone in a sound-insulated room in the phonetics laboratory at the University of Massachusetts at Amherst.[7] Words were read in an oral word frame: [ere 'X' ᵈjeɨ] 'say 'X' again'. In this sentence, the main stress fell on the final vowel of the bisyllabic CVCV word. Nasal harmony did not extend across word boundaries, leaving the medial word unaffected by the frame words. Words were read at a normal speech rate grouped in random batches of 12 different words. Of each batch of 12 items, the first and last token were discarded, as intonation and emphasis was sometimes affected at these boundaries. Breaks in recording were taken as needed. A total of six valid repetitions of each word were recorded.

### 4.2.2 Instrumental analysis

The recordings were digitized using a sampling rate of 20,000 Hz. Durations of various of the segmental components were measured on a Kay Elemetrics Computerized Speech Lab Model 4300 at the University of California, Santa Cruz, making reference to both waveforms and spectrograms. On each digitized token, four points were tagged. The criteria by which these points were identified are described below, and they are illustrated on the waveform and spectrogram in (8) showing the VCV segment of the oral word [pokó] 'to touch'. The first point (a) marks 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. The second point (b) marks the end of voicing into the stop, signalled by the end of periodic oscillations after the first vowel in the waveform. The third point (c) marks the release of stop closure. This is signalled by 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.

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[7] I am grateful to John Kingston for permission to use the Phonetic Lab at the University of Massachusetts and for help with setting up the study as well as providing comments on analysis of the data. I would also like to express thanks to Jaye Padgett and John Ohala for discussion of aspects of the data analysis and to John McCarthy for sponsoring my visit to the University of Massachusetts. Any errors are entirely my own and are not a reflection on any of these individuals. Thanks to Manuel Ferreira for consultation on the Guaraní language.

Because of the root-final stress in the bisyllabic words, the amplitude of the second vowel was much greater than the first, often resulting in a very weak spectrographic image for the first vowel. 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 spectrograms shown in this chapter have undergone this double gain. If the increased amplitude was still not sufficient to reveal the boundaries of the first vowel, pre-emphasis was applied to flatten the spectral shape of the voiced speech signal and bring out the spectral characteristics of the higher frequencies with similar resolution to those of the lower frequencies. This made visible the areas of the signal where formant energy occurred. Since the resulting spectrogram distorted other properties of the signal, such as voicing, the other points were marked before pre-emphasis was performed (pre-emphasis is not performed in the spectrogram in (8)).

From the four marked points on each token, various durations were measured. The following report focuses on five of these durations: (i) Closure Voicing, which measures from initiation of stop closure (8a) to the end of voicing after the first vowel (8b); (ii) Closure Duration, measuring from initiation of closure (8a) to the release of closure (8c). (iii) Voiceless Closure Duration, from the point of end of voicing into the stop (8b) to the release of closure (8c); (iv) Voice Onset Time, measuring from the release of stop closure (8c) to the onset of voicing (8d); and (v) Total Voiceless Period, the duration from the end of voicing into the stop (8b) to the onset of voicing in the following vowel (8d). Each of these durations were measured for all six tokens of each oral word and then averaged and compared with the average for the nasal pair word. Comparisons were made by oral versus nasal words across and within places of articulation for the medial stop. Computations and statistical analysis were performed using Excel 5.0 software. The analyses of variance in oral versus nasal words were tested using a two-factor Anova. The results are reported on and interpreted in the following section.

### 4.3 Results

The results of the study are presented at three levels of detail. First I summarize the general patterns of closure and voice timing common to oral and nasal words. Then I discuss different properties of timing in oral versus nasal words taken as a whole across



the sample, followed in each case by an examination of the effect of place of articulation on any timing differences. It will emerge that there are interesting differences in the timing properties of voiceless stops in oral versus nasal words, but words with velar stops are often the exception to the generalizations. This, I propose, is explained by a threshold effect for /k/, which I suggest achieves a sufficient or maximal voice onset time.

#### 4.3.1 General patterns

I begin by remarking on the general patterning of voiceless stops in both oral and nasal words. One focal observation is that /p, t, k/ are typically realized as oral obstruent stops in both oral and nasal spans. In nasal spans it is not the case that they become fully voiced or fully nasal during the closure, nor are they produced as voiceless nasal stops. The absence of voicing for a substantial period during the stop is clearly discernible from both the spectrogram and waveform. The orality is evident from the gap during the closure, indicating the absence of the energy that would be produced by nasal airflow. The stops are also accompanied by a robust burst, showing that pressure has accumulated behind the closure in the oral cavity, and so air has not escaped freely through the nasal passage. A sample spectrogram and waveform for the nasal word [õkẽ́] ‘door’ is shown in (9).

This acoustic information confirms the transparency effect that has been reported in the Guaraní grammars. The surface orality of the 'transparent' voiceless stops is consistent with the analysis of transparency as an opacity effect: the output representation posited for these segments is an oral one, they are truly non-nasal at the surface. These transparent segments cannot be analyzed as instances of 'false transparency' where the velum remains lowered throughout the full duration of the segment.[8]

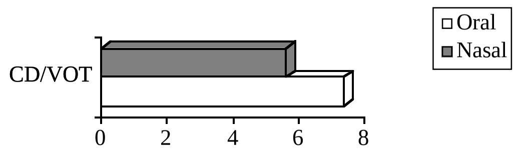
Another point on the subject of common acoustic patterns concerns voice timing. In both oral and nasal environments, voicing persists part-way into the stop closure. The closure voicing is followed by a period of voicelessness, which begins during the closure and persists for a period after the release. Although this basic model characterizes voiceless stops in both contexts, some of the details of the timing differ by environment. These differences are discussed below. First I outline the effects that were discovered to be conditioned by nasal environments, and then by comparing aspects that remain fixed, I posit a defining acoustic property of voiceless stops.

### 4.3.2 Effect 1: Ratio of closure duration to voice onset time

One of the major context-induced effects found in this study is that the average ratio of closure duration to voice onset time (CD/VOT), i.e. the average of the CD/VOT ratios, is overall significantly smaller in nasal contexts than in oral ones. The reason that the CD/VOT ratio was calculated rather than only evaluating closure and voice onset time separately was to control for any word-to-word or token-to-token variation in speaking rate. The individual contributions of the differences in closure length and voice onset time will be examined presently. The difference in the ratios of closure duration over voice onset time are given in (10), taken across all three places of articulation. The average for oral contexts of 7.375 is greater than the nasal average of 5.597, a difference which is statistically significant ($p < 0.0001$).

8 A cursory examination of some audio recordings of Desano (Tucanoan; Colombia) showed the same basic surface transparent character for voiceless stops in nasal morphemes (recordings were made by Jonathan Kaye 1965-1966). I am grateful to Jonathan Kaye for making his recordings of Desano available to me.

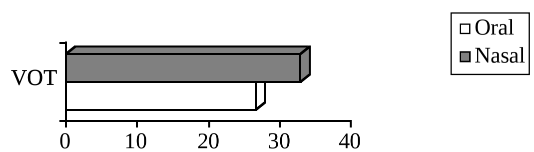
(10) Closure duration/Voice onset time (CD/VOT): results across sample




| | **Oral** | > | **Nasal** | |
|---|---|---|---|---|
| Number of tokens | 108 | | 108 | |
| Variance | 9.990 | | 6.109 | |
| Average CD/VOT | **7.375** | > | **5.597** | *df* =1, *F* =34.02, *p* < 0.0001 |

The cause for the difference in the ratio of closure to voice onset time can be traced to both of the logically possible contributors: in nasal contexts voice onset times are longer and closure durations are shorter. The average voice onset times are given in (11): 26.64 msec. in oral words and 32.80 msec. in nasal words ($p$ <0.0001). The greater values in nasal words give a greater denominator in CD/VOT, yielding smaller ratios for nasal environments.

(11) Greater VOT in nasal contexts.

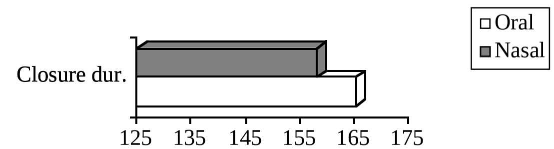



| | **Oral** | < | **Nasal** | |
|---|---|---|---|---|
| Number of tokens | 108 | | 108 | |
| Variance | 0.13 | | 0.14 | |
| Avg. VOT (msec.) | **26.64** | < | **32.80** | *df* =1, *F* =26.88, *p* < 0.0001 |

Average closure durations for the intervocalic voiceless stops are shown in (12). The average closure is longer in oral environments (165.37 msec.) than in nasal ones (158.20 msec.; $p$ <0.005). The shorter closures in nasal words give a smaller numerator in the CD/VOT ratio, contributing to the smaller nasal CD/VOT values.



(12) Shorter closure durations in nasal contexts.

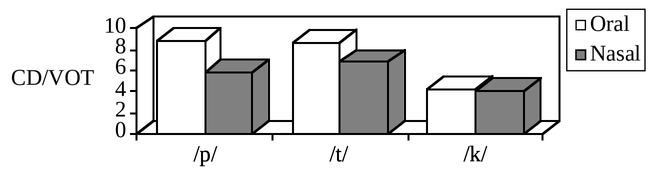



| | **Oral** | > | **Nasal** | |
|---|---|---|---|---|
| Number of tokens | 108 | | 108 | |
| Variance | 0.38 | | 0.30 | |
| Avg. closure dur. (msec.) | **165.37** | > | **158.20** | *df* =1, *F* =8.30, *p* < 0.005 |

So far we have considered results across the entire sample of data, but when the tokens are sorted by place of articulation of the medial stops, we find that place interacts with the difference in CD/VOT in nasal versus oral words. The results for closure duration over voice onset time for each place of articulation are displayed in (13). For both [p] and [t], the ratio is significantly greater in oral contexts than in nasal ones. For [p] the difference is greatest, with an average value in oral words of 8.880 comparing with an average of 5.859 in nasal words ($p$ <0.0001). The figures for [t] are roughly similar: oral average 8.670 versus nasal average 6.838 ($p$ <0.0001).[9] The velar, [k], is the odd one out, having no significant difference in CD/VOT in oral versus nasal environments (oral average 4.241 and nasal average 4.101; $p$ =0.5).

9 In computations by place of articulation, data from all seven words pairs for [t] are included, giving a total of 84 tokens (42 for each of oral and nasal with six repetitions of each of the seven words). The six word pairs for [p] and [k] yield 72 tokens for each of these places. In oral/nasal comparisons combining data from all three places of articulation, durations for only six word pairs for [t] were included in order to balance with the number of tokens for [p] and [k], giving a total of 216 tokens (3 x 72). The word pair for [t] excluded in comparisons across all places of articulation is [patí]/[katĩ̯] chosen at random.

(13) Closure duration/Voice onset time by place of articulation.




| | /**p**/ significant | | /**t**/ significant | | /**k**/ not significant | |
|---|---|---|---|---|---|---|
| | **Oral** > | **Nasal** | **Oral** > | **Nasal** | **Oral** | **Nasal** |
| No. of tokens | 36 | 36 | 42 | 42 | 36 | 36 |
| Variance | 7.171 | 6.950 | 7.051 | 6.076 | 0.866 | 1.368 |
| Avg. CD/VOT | **8.880** > | **5.859** | **8.670** > | **6.838** | **4.241** | **4.101** |
| | *df* =1, *p* <0.0001 | *F* =40.73, | *df* =1, *p* <0.0001 | *F* =25.93, | *df* =1, *p* =0.5 | *F* =0.45, |

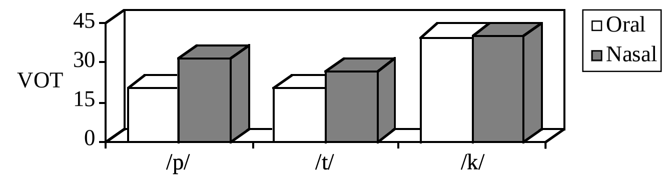
In addition to not having a different CD/VOT value in oral versus nasal contexts, [k] is remarkable in two other respects. One feature clearly visible on the bar graph in (13) is that the value of CD/VOT for [k] is much smaller than for [p] or [t]. The other point is that the variance for [k] is much smaller than for the other stops. Variance for the velar is in the neighborhood of about 1, but for [p] and [t] the variance is as high as 6 to 7. This suggests that aspects of the timing with velars are highly fixed in comparison to the other stops. I will return to these points after looking at a few more of the results sorted by place of articulation.

(14) gives voice onset times by place of articulation. Once again [p] and [t] conform to the general pattern, exhibiting significantly greater voice onset times in nasal contexts (oral average 20.59 msec. for [p] and 20.38 msec. for [t] versus nasal average 31.47 msec. for [p] and 26.65 msec. for [t]; $p$ <0.0001). [k], on the other hand, does not have significantly different voice onset times in oral versus nasal words; its voice onset time is consistently about 40 msec.. Notice that voice onset times for [k] far exceed those of the anterior stops. The occurrence of longer voice onset times for velars than for anterior stops accords with the findings of other studies on place and voice onset time; Lisker and Abramson (1964) were the first to report this observation. In the Guaraní data, this difference by place is such that even in oral environments, voice onset times for [k] are about 10 msec. longer than for nasal bursts in other places of



articulation. It may be noted that the variances here are at least twice as great in nasal than in oral words. This difference will be discussed in section 4.4.

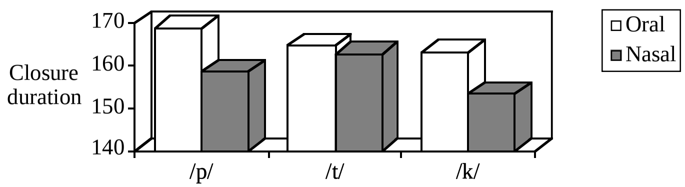
(14) Voice onset time by place of articulation.




| | /**p**/ significant | | /**t**/ significant | | /**k**/ not significant | |
|---|---|---|---|---|---|---|
| | **Oral** < | **Nasal** | **Oral** < | **Nasal** | **Oral** | **Nasal** |
| No.of tokens | 36 | 36 | 42 | 42 | 36 | 36 |
| Variance | 0.036 | 0.14 | 0.029 | 0.076 | 0.059 | 0.12 |
| Avg. VOT (msec.) | **20.59** < | **31.47** | **20.38** < | **26.65** | **39.80** | **40.11** |
| | *df* =1 *p* <0.0001 | *F* =38.29 | *df* =1 *p* <0.0001 | *F* =27.44 | *df* =1 *p* =0.87 | *F* =0.03 |

The values for closure duration by place of articulation are shown in (15). Here [p] and [k] are significantly different with shorter closures in nasal contexts (oral average for [p] 168.86 msec. and for [k] 163.17 msec. versus nasal average for [p] 158.64 msec. and for [k] 153.47 msec. $p$ <0.005). Interestingly, closure duration for [t] is not significantly shorter in nasal words. In section 4.5 we will see that this is connected to some tokens for nasal words with [t] having two burst events, which produced increased closure durations. An alternative way in which a distinction is achieved for the closure properties of [t] in nasal contexts is discussed in the next section on closure voicing.

(15) Closure duration by place of articulation.




| | /p/ significant | | /t/ not significant | | /k/ significant | |
|---|---|---|---|---|---|---|
| | **Oral** > | **Nasal** | **Oral** | **Nasal** | **Oral** > | **Nasal** |
| No. of tokens | 36 | 36 | 42 | 42 | 36 | 36 |
| Variance | 0.29 | 0.25 | 0.27 | 0.37 | 0.56 | 0.22 |
| Avg. closure duration (msec.) | **168.86>** | **158.64** | **164.67** | **162.83** | **163.17>** | **153.47** |
| | *df* =1 $p$ <0.005 | $F$ =8.69 | *df* =1 $p$ =0.54 | $F$ =0.38 | *df* =1 $p$ <0.005 | $F$ =8.69 |

To summarize, the findings reported so far are that the ratio of closure duration to voice onset time is greater in oral contexts than in nasal ones. A strong contributing factor is longer voice onset times in nasal words ($p$ <0.0001) and a somewhat weaker factor is shorter closure durations in nasal words ($p$ <0.005). The velar stop proves to be somewhat exceptional in not having a significantly different CD/VOT average in nasal versus oral words or a significantly different average voice onset time.

The general pattern that has been identified is that in nasal intervocalic environments, voiceless stops have longer voice onset times and shorter closures. It is interesting that there is an inverse relationship in the timing of the two segments: longer closures cooccur with shorter voice onsets. We will see ahead that this is a consequence of the voiceless period of the stop undergoing a shift to the right in nasal environments. However, velar stops are the exception. This, I suggest, is related to the fact that velars make the most successful voiceless obstruent stops. In comparison to the anterior stops, the back site of constriction for a velar produces a smaller cavity behind the closure, favoring the build-up of pressure needed to inhibit voicing. The effect of this was apparent in (14), where [k] had greater voice onset times than either [p] or [t] (correlating with differences by place for voice onset times in other languages; Lisker and Abramson 1964). Recall also that [k] exhibited comparatively minimal variance in the CD/VOT ratio, indicating that aspects of the timing in the production of [k] are considerably more

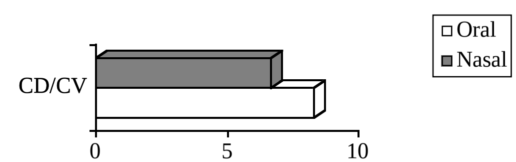


fixed than in [p] or [t]. I hypothesize that the separate behavior of [k] in nasal contexts is the consequence of a threshold effect for the length of its VOT. The voiceless period in anterior stops shifts to the right in nasal environments. In the case of [k], a shift does not take place to produce a longer voice onset time, because it has achieved a threshold in its duration. This threshold could be understood in one of two ways, which are open to empirical verification in further work. It could either be that [k] already has a *maximal* voice onset time, preventing any further carry-over into the following vowel or [k] has a *sufficient* voice onset time, one that does not need to be enhanced when the voiceless portion of the closure is shortened. These points will be synthesized after examination of the second major timing effect in oral versus nasal contexts.

### 4.3.3 Effect 2: Ratio of closure duration to closure voicing duration

The second main effect discovered in the production of voiceless stops in oral versus nasal words is that the average ratio of closure duration to closure voicing duration (CD/CV), i.e. the average of the CD/CV ratios, is overall significantly smaller in nasal words. This means that a greater portion of the closure is voiced in a nasal vocalic environment. The averages are given in (16). The oral ratio of 8.29 exceeds the nasal one of 6.66 ($p$ <0.02).

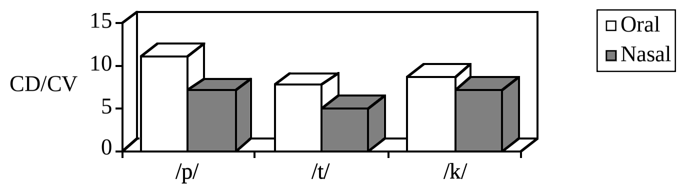
(16) Closure duration/Closure voicing duration (CD/CV): results across sample.




| | **Oral** > | **Nasal** | |
|---|---|---|---|
| Number of tokens | 108 | 108 | |
| Variance | 34.10 | 15.27 | |
| Average CD/CV | **8.29** > | **6.66** | *df* =1, $F$ =5.89, $p$ < 0.02 |

When examined by place of articulation, it emerges that the difference in the closure duration to closure voicing ratios holds specifically of tokens with [t]. The averages are shown in (17), with an average value for oral tokens of 7.83 and for nasal tokens of 5.09. The difference in the cases of words with [p] and [k] is not statistically significant.[10]

(17) Closure duration/Closure voicing duration (CD/CV) by place of articulation.



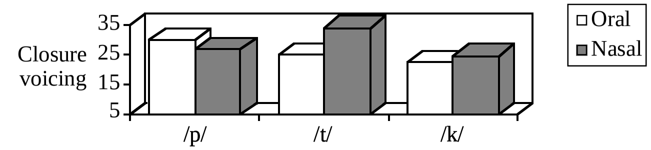

| | /**p**/ not significant | | /**t**/ significant | | /**k**/ not significant | |
|---|---|---|---|---|---|---|
| | **Oral** | **Nasal** | **Oral** | **Nasal** | **Oral** > | **Nasal** |
| No. of tokens | 36 | 36 | 36 | 36 | 36 | 36 |
| Variance | 7.00 | 6.69 | 13.20 | 1.90 | 19.50 | 10.27 |
| Avg. CD/CV | **11.21** | **7.11** | **7.83** > | **5.09** | **8.83** | **7.28** |
| | *df* =1, *p* =0.56 | *F* =0.34 | *df* =1, *p* <0.0001 | *F* =29.06 | *df* =1, *p* =0.058 | *F* =3.73 |

Although closure durations were found to be shorter in nasal words for [p] and [k] (see (15)), giving a smaller numerator for CD/CV, this was not sufficient to produce a significant difference in the CD/CV ratio. Recall, however, that [t] did not have a significantly different average closure duration in oral versus nasal contexts. For [t], there was found to be more closure voicing in nasal environments yielding an increase in the voiced portion of the closure. This is shown in (18). Between oral vowels the average closure voicing for [t] is 24.78 msec. and in nasal words this increases to 34.07 msec. ($p$ <0.005). [p] and [k] do not have a significant difference in closure voicing in nasal versus oral contexts, which accords with their lack of difference in CD/CV.

10 Only six of the seven word pairs for [t] are reported here. The seventh word pair ([mbotɨ́], [motɨ̃́]) was aberrant in displaying an unusually high variance (363.07 for oral tokens, 143.63 in nasal tokens). With this word pair included, the difference for CD/CV in oral versus nasal words was still significant: number of tokens for each of oral and nasal = 42; average 8.85 oral, 5.98 nasal; variance 61.84 oral, 24.73 nasal; $df$ =1, $F$ =4.25, $p$ =0.04. In general, the oral tokens exhibit a higher variance for the CD/CV ratio than nasal tokens, although the cause for this is unclear.



(18) Greater closure voicing for /t/ in nasal contexts.

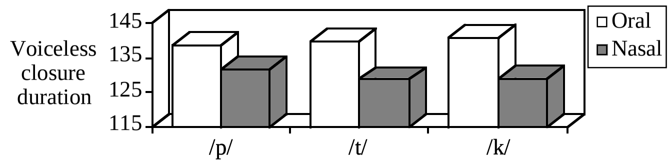



| | /**p**/ not significant | | /**t**/ significant | | /**k**/ not significant | |
|---|---|---|---|---|---|---|
| | **Oral** | **Nasal** | **Oral** < | **Nasal** | **Oral** | **Nasal** |
| No. of tokens | 36 | 36 | 42 | 42 | 36 | 36 |
| Variance | 0.24 | 0.092 | 0.12 | 0.35 | 0.097 | 0.090 |
| Avg. closure voicing (msec.) | **29.98** | **26.95** | **24.78** < | **34.07** | **22.42** | **24.54** |
| | *df* =1, *p* =0.1 | *F* =2.66 | *df* =1, *p* <0.005 | *F* =8.92 | *df* =1, *p* =0.2 | *F* =1.69 |

A related property that holds consistently across all places of articulation is a shorter duration of the voiceless period of the closure in nasal contexts. This is illustrated in (19). Between oral vowels, the voiceless closure is around 140 msec. in duration, while in nasal contexts this falls to about 130 msec..[11]

11 It should be noted that on some points of comparison, including duration of voiceless closure, the analysis of variance indicated that within the set of words for a given place of articulation, an interaction was registered with individual word pairs. This means that particular word pairs sometimes showed a stronger or weaker effect for the oral/nasal contrast in question. It is possible that the height of the flanking vowels was an influencing factor here, although since the study was not designed to test this, we do not have enough information from the data to tell for certain. Examination of the results by word did not reveal any obviously systematic effect of vowel height, but this could be investigated more fully with a set of word pairs specifically constructed to compare the effect of adjacent vowel quality.

(19) Voiceless closure shorter in nasal contexts for all places of articulation.

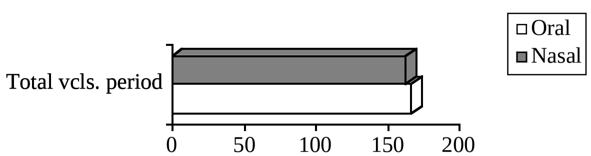



| | /p/ significant | | /t/ significant | | /k/ significant | |
|---|---|---|---|---|---|---|
| | **Oral >** | **Nasal** | **Oral >** | **Nasal** | **Oral >** | **Nasal** |
| No. of tokens | 36 | 36 | 42 | 42 | 36 | 36 |
| Variance | 0.40 | 0.27 | 0.26 | 0.51 | 0.46 | 0.18 |
| Avg. voiceless closure (msec.) | **138.88>** | **131.69** | **139.89>** | **128.76** | **140.76>** | **128.93** |
| | *df* =1 $p<0.04$ | $F=4.50$ | *df* =1 $p<0.005$ | $F=8.46$ | *df* =1 $p<0.005$ | $F=11.51$ |

### 4.3.4 A fixed property: Total period of voicelessness

The last finding I will report on concerns a fixed property of voiceless stops in oral and nasal contexts. Across the sample of data, it was found that the total period of voicelessness for stops does not differ significantly in oral versus nasal words. The values are given in (20) falling around 165 msec. ($p=0.14$).

(20) Total period of voicelessness is not different: results across sample.

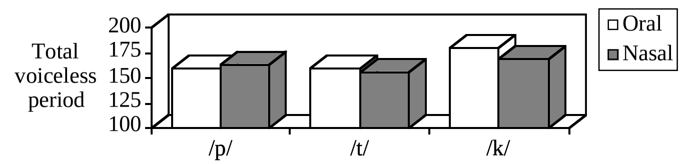



| | **Oral** | **Nasal** | |
|---|---|---|---|
| Number of tokens | 108 | 108 | |
| Variance | 0.51 | 0.40 | |
| Avg. voiceless dur. (msec.) | **166.31** | **162.27** | *df* =1, $F=2.23$, $p=0.14$ |



Interestingly, when we compare the averages for total period of voicelessness by place of articulation, [k] is once again singled out in contrast to [p] and [t]. This is shown in (21). [p] and [t] conform to the generalization in (20), with no significant difference in their total voiceless period by oral/nasal context. [k], however, has a longer total voiceless period in oral words than in nasal ones. Further, the total period of voicelessness for [k] exceeds that of the anterior stops in oral or nasal environments.

(21) Total period of voicelessness by place of articulation.



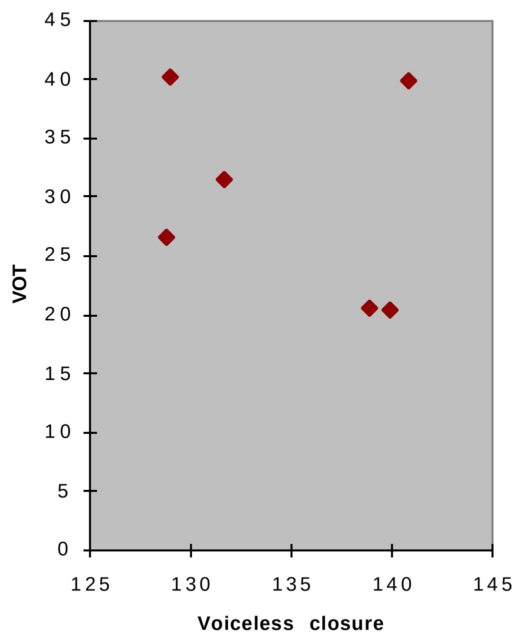

| | /p/ not significant | | /t/ not significant | | /k/ significant | |
|---|---|---|---|---|---|---|
| | **Oral** | **Nasal** | **Oral** | **Nasal** | **Oral >** | **Nasal** |
| No. of tokens | 36 | 36 | 42 | 42 | 36 | 36 |
| Variance | 0.48 | 0.26 | 0.26 | 0.55 | 0.56 | 0.25 |
| Avg. voiceless duration (msec.) | **159.48** | **163.16** | **160.27** | **155.41** | **180.56>** | **169.04** |
| | *df* =1 $p=0.30$ | $F=1.11$ | *df* =1 $p=0.23$ | $F=1.47$ | *df* =1 $p<0.005$ | $F=10.3$ |

To review, we have seen that overall the total period of voicelessness is not significantly different in oral versus nasal words, but when we take place of articulation into consideration, it emerges that [k] has shorter voiceless periods in nasal words. This is reminiscent of the threshold effect in the voice onset time which was hypothesized earlier for [k].

### 4.4 Discussion

I now will put the various findings together to construct an integrated picture of what timing changes take place in voiceless stops between nasal vowels. To begin, the chart in (22) synthesizes the correlation observed between the voiceless closure duration and voice onset time in oral versus nasal contexts for each place of articulation. In oral contexts the duration of voiceless closure averages about 140 msec. across all places. For the anterior stops [p, t], the VOT is about 20 msec. in oral tokens, and for [k], the average VOT is considerably longer, at about 40 msec. In nasal tokens, these averages change so that voiceless closure decreases and VOT increases, except in the case of [k]. For [p] and [t], the average voiceless closure duration drops to about 130 msec. and the VOT increases to the neighborhood of 25-30 msec. The decrease in voiceless closure and corresponding increase in VOT is apparent in the negative slope of the lines connecting the oral and nasal plots of these average values for [p] and [t]. In the case of [k] in nasal tokens, the average voiceless closure exhibits a fall to about 128 msec., matching that of the anterior stops; however, the average voice onset time remains essentially constant, holding at about 40 msec.

(22) Average voiceless closure plotted against average VOT



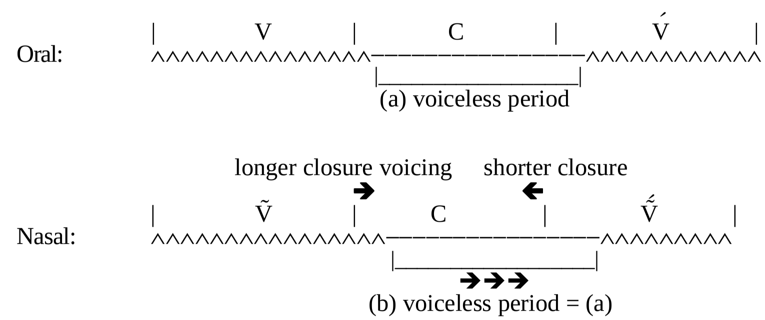

Legend: $[p, t, k]_o$ = [p, t, k] (respectively) in oral context

$[p, t, k]_n$ = [p, t, k] (respectively) in nasal context



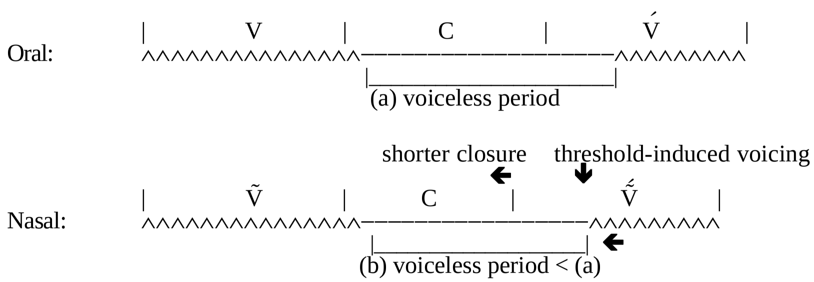
With these results in mind, I will turn to an interpretation of the findings. Timing in oral versus nasal environments in the VCV segment of the word is represented schematically in (23). Vertical lines on either side of the consonant (C) mark the points of initiation and release of closure, respectively. Below the VCV, zigzags signify voicing and a straight horizontal line represents voicelessness. A central finding of the study is that there is a fixed period of voicelessness for voiceless stops, which does not change across oral and nasal environments. It may be that a fixed duration of voicelessness is a significant property for perception of voiceless stops, at least in Guaraní. In the oral word in (23), the voiceless portion is marked as the period (a) and in the nasal word it is marked as (b). (a) and (b) are equal in length — this property does not differ in oral and nasal words. What does change in nasal words is that the voiceless closure duration decreases, either because of a shorter closure ([p, k]) or longer closure voicing ([t]). The result is that to preserve the fixed duration of voicelessness, the voiceless period shifts to the right to extend farther into the following vowel. This produces the increased voice onset time in nasal words.

(23) Schematic representation of shift of voiceless period.




The above situation describes what has been observed for the anterior stops [p] and [t]. [k] behaves somewhat differently, and the schematic representations corresponding to this segment are shown in (24). Recall that of the three places of articulation, velars make the best voiceless stops: their back closure provides conditions producing the longest voice onset times. I have suggested that the voice onset time for [k] has reached a threshold in Guaraní, that is, it will not exceed about 40 msec.. This means that when the closure duration for [k] is cinched in nasal environments, the voiceless period will not shift to the right, because it has reached the limit of its extension into the following vowel. As a result, the voiceless period (a) between oral vowels is greater than the voiceless period (b) between nasal vowels.

(24) Schematic representation of threshold effect for /k/.




It was noted earlier that the threshold effect in the velar voice onset time could be one of *sufficient* length. From this perspective, the duration of post-release voicelessness would be sufficient to signal the voiceless quality of the stop, even under conditions of a shorter voiceless period during the closure. Avoidance of further intrusion on the vowel would then prevent a rightward shift in the voiceless period from taking place. The failure of the voice onset time of the anterior stops to meet the sufficiency requirement would explain the shift with these stops. It also is conceivable that the threshold is a result of velar voice onset times reaching a *maximal* length. Under this view, the threshold effect in the velar post-release voicelessness 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 msec.. It is also possible that a maximal threshold arises simply as an aerodynamic effect, whereby the relatively unconstricted airflow during the vowel induces spontaneous voicing after no longer than 40 msec.. In either case, the conception of a threshold effect for [k] as the most robust voiceless stop explains why we see its separate behavior. [k] follows the core pattern of reducing closure duration between nasal vowels. However, since the velar stop does not extend its voice onset time, we do not find a difference in oral versus nasal words for voice onset time or the ratio of the closure duration to VOT. Also, because the voice onset time has reached its threshold, [k] must lose on preserving the length of its total voiceless period in nasal words, and so the total voiceless duration is shorter just in the case of velar stops.



This account explains differences in timing as a result of a shift of voicelessness to the right in order to maintain a fixed voiceless period, and the exceptionality of velar stops is interpreted as the consequence of a threshold effect for voiceless stops articulated with a back closure. The outcomes predicted under this account fit well with the data. A property that currently stands only as an observed characteristic is the decrease in the length of voiceless closure between nasal vowels. When this is achieved by an increase in closure voicing (in the case of [t]), this may be explained as a post-nasal voicing effect, which has been well-documented in the phonetic literature (see, for example, Westbury 1983; Westbury and Keating 1986; Ohala and Ohala 1991, 1993; Bell-Berti 1993; Hayes 1995; Pater 1996, in press; 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 duration of voiceless closure is instead produced by a shorter closure duration. The occurrence of shorter closures in nasal environments may be connected to the general finding across languages that nasal vowels are longer than their oral counterparts (see Whalen and Beddor 1989 and references cited therein). It is conceivable that the greater length of the 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, for example, Ladefoged 1993; Laver 1994).[12]

The results of this study raise some other directions for future research. On Guaraní, it would be productive to replicate the study of timing effects in oral versus nasal words with a larger base of subjects in order to verify that the generalizations hold for the language. In other languages with contrasting oral/nasal vocalic environments, it would be worth investigating whether a fixed period for voicelessness occurs for voiceless stops. The findings of the present study suggest that a fixed voiceless period is a property that contributes to defining voiceless stops, at least in Guaraní. Further work is needed to determine whether this phonetic characteristic is universal or language-particular.

An interesting implication of the contextual variation in timing found in this work is that it confirms the need to characterize the phonetic implementation of phonological features as well as the overlap of articulations from one segment to the next (see, for example, Chomsky and Halle 1968; Pierrehumbert 1980; Browman and Goldstein 1986, 1989, 1990; Keating 1988, 1990; Cohn 1990, 1993a, b; Huffman 1990, 1993; Kingston

12 Thanks to John Ohala for pointing out the possible connection of reduced length in onset consonant closure to the increase in nasal vowel duration.

1990; Kingston and Diehl 1994; foundation is provided by Öhman 1966, 1967). Various models of phonetic implementation have been proposed which map from an abstract phonological representation to a more concrete continuous sequence of timed articulations or gestures, and I will briefly consider the Guaraní results in relation to some of these models.

Some analysts have argued that the phonetic correlates of features are coordinated with other articulations in systematic ways. For example, Kingston's (1990) 'binding principle' 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 (1990) 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 both Kingston and Huffman's proposals in that the point of release of voiceless stops in oral and nasal contexts was consistently oral and voiceless. The oral closures in these data, however, rule out a possible interpretation of voiceless stop transparency extending Huffman's proposal in which the closure of the stop is nasal and only the release is oral.[13] In regard to voice timing, recall from (14) that the variances for VOT in nasal tokens were found to be at least twice that in oral tokens at all places of articulation. If voice onset time is a function of when the glottis closes relative to the stop release, then this indicates that the coordination of the glottal closure and oral release is much more variable in nasal tokens. This significant a degree of difference in variance cannot be attributed simply to the increase in voice onset time in nasal words; further, this difference was specific to VOT: variances for closure durations did not differ systematically for oral versus nasal words (see (15)). Kingston (personal communication) suggests that the variability in nasal tokens may come about from the shift in the glottal articulation having become 'unbound' from the oral articulation. This unbinding could be caused by the shift in the glottal articulation from the onset of closure which takes place from the delay in glottal opening (occurring in [t]). This

13 Thanks to John Kingston for bringing this point to my attention.



explanation posits a connection in the timing of the glottal articulation to both the onset and release of closure. In the case of stops which have a shorter closure duration in nasal contexts, the earlier point of release and the shift of the glottal articulation to persist longer into the vowel may also unbind the glottal and oral articulations.

An important property of the phonetic implementation of [-voice] found in this study is that the duration of voicelessness remains fixed and shifts into the following vowel when the voiceless segment of the closure decreases. This kind of phonetic behavior indicates that it is not the case that the boundaries of the period of voicelessness are fixed in relation to oral gestures, rather there is some room for movement. This rightward shift of the voiceless gesture fits well with the representations of Articulatory Phonology, where glottal features are modelled as durational gestures arrayed on a tier for laryngeal articulations (Browman and Goldstein 1986, 1989, 1990). These may be coordinated with gestures on other tiers, but they have some flexibility in their timing. In nasal contexts in Guaraní, the early onset of release or increase in closure voicing pushes the voiceless gesture to the right, producing a greater voice onset time into the succeeding vowel. The relative independence of the laryngeal tier and the tier representing oral constriction readily reflects this kind of shift in the overlap from one segment to the next.

The need for some flexibility in phonetic implementation is also recognized by Kingston and Diehl (1994). In their work on the realization of the feature [voice], they 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 demands of minimizing articulatory effort with listener-oriented maximization of perceptibility. If we take as a hypothesis that in the general case in Guaraní, a fixed duration of voicelessness is needed for perceptibility of voiceless stops, then the shift of the voiceless period when voiceless closure decreases can be characterized as a controlled adjustment to accommodate listener-oriented needs. This shift still obeys the constraint of producing voicelessness at the point of release.[14] In the case of [k], the voice onset time is conjectured to have reached a threshold. This threshold is listener-oriented if the voice onset time 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

14 It has been suggested to me by Bruce Hayes that the increase in the voice onset time in nasal tokens could be a consequence of a greater glottal abduction to inhibit post-nasal voicing. While this is an interesting factor to consider and certainly merits further investigation, the fixed duration of the voiceless period across oral and nasal tokens suggests that there is actually a controlled shift in glottal timing taking place.

voice onset as a consequence of aerodynamic factors, this would be a speaker-oriented effect. In either case, the fixed onset of voicing in the vowel following [k] is moderated by minimization of articulatory effort. Kingston and Diehl's notion of a speaker-controlled phonetics limited by certain principles and constraints thus provides a good framework in which to characterize the competing demands in the realization of Guaraní voiceless stops in nasal contexts as well as the contribution of these demands to the different outcomes for anterior versus velar stops. The Guaraní data show that some degree of flexibility in timing and an acknowledgement of various and sometime conflicting realizational requirements is necessary in any theory of phonetic implementation.

### 4.5 Two-burst events

In this last section, I outline a somewhat different pattern observed in the release of a small set of voiceless stops in nasal contexts. In these cases, the voiceless stops appear to have two rather than one events associated with the burst. Some sample spectrograms are given in (25) and (26) below.

The spectrogram in (25), which shows the VCV portion of [hãtã́] 'hard' illustrates one kind of pattern seen in these exceptional tokens. Here there are two apparently separate burst spikes. In tokens like this, the burst spikes seem to be far enough apart to rule out an occurrence of simply a sloppy burst (as, for example, was found in some tokens of [k]). The spectrogram for [pɨ̃tṹ] 'dark' in (26) shows a second kind of two-event production. Here the main burst spike is preceded by a period 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; however, a fuller understanding of the articulatory action producing this first burst requires further investigation. Although it is not clear why, tokens exhibiting one of these different spectrographic patterns were restricted primarily to instances of [t] in nasal words. It should be noted that when this kind of pattern occurred, the duration from the initiation of closure to the second burst event was often longer than the regular one-burst-event tokens for [t]. Although the two-event pattern occurred in only some of the nasal words with [t], 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 shorter closures in nasal words (see (15)).

An intriguing feature of the two-burst phenomena is their apparent correlation to nasal tokens. It is conceivable that some aspect of the timing of velic closure and opening may contribute to these occurrences. In order to test the hypothesis that the two-event patterns are connected to the nasal context, it is necessary to make use of instrumental techniques which give more information about velum position during production of the stop. Photodetector devices, which register the relative amount of light that passes through an opening, would provide direct information about velic aperture (see, e.g., Ohala 1971 on the Nasograph; Dalston 1982). A less invasive alternative would be to measure nasal airflow (see, e.g., Benguerel 1974; Cohn 1990; Huffman 1990; Gerfen 1996). One of the most successful means of measuring airflow is with a split mask that covers the nose and mouth. The mask is divided to detect oral and nasal airflow separately, and a reading is achieved by directing the air into a device to measure air pressure which is used to convert the differences in airflow into a varying electric signal. While this alternative may be more comfortable for the subjects, it only provides information about velum position to the extent that it may be extrapolated from nasal airflow readings; photodetectors give more direct evidence. A variety of other investigative techniques are outlined by Krakow and Huffman (1993), and an instrumental study of Guaraní making use of one of these devices would be a worthy project for future research.

## 4.6 Appendix: Word pairs

**/p/**

| | | | |
|---|---|---|---|
| 1. | /rupá/ | [rupá] | 'bed' (1st poss.) |
| | /nupã́/ | [nũpã́] | 'to hit' |
| 2. | /ᵈjopɨ́/ | [ᵈʒopɨ́] | 'to itch, sting' |
| | /popɨ̃́/ | [põpɨ̃́] | 'to peel, strip' |
| 3. | /kepé/ | [kepé] | 'asleep' |
| | /mbopẽ́/ | [mõpẽ́] | 'he/she broke' |
| 4. | /pepé/ | [pepé] | 'to flutter, flap wings' (lit.) |
| | /ᵈjepẽ́/ | [ɲẽpẽ́] | 'to break' |
| 5. | /ᵈjapɨ́/ | [ᵈʒõpɨ́] | 'to throw, shoot at' |
| | /ᵈjapɨ̃́/ | [ɲãpɨ̃́] | 'to cut hair' |
| 6. | /hapɨ́/ | [hapɨ́] | 'to catch fire' |
| | /ʃapɨ̃́/ | [ʃãpɨ̃́] | 'defective, amputated, cut off' |

**/t/**

| | | | |
|---|---|---|---|
| 1. | /kutú/ | [kutú] | 'to stick (with), prick, strike' |
| | /pɨtṹ/ | [pɨ̃tṹ] | 'dark' |
| 2. | /ɨtá/ | [ɨtá] | 'stone, rock' |
| | /ɨtã́/ | [ɨ̃tã́] | 'to swim' |
| 3. | /mbotɨ́/ | [mbotɨ́] | 'to close, shut' |
| | /mbotɨ̃́/ | [mõtɨ̃́] | 'to cause shame' |
| 4. | /potá/ | [potá] | 'to want, desire' |
| | /tetã́/ | [tẽtã́] | 'nation, country' |
| 5. | /tatɨ́/ | [tatɨ́] | 'daughter-in-law' |
| | /tatɨ̃́/ | [tãtɨ̃́] | 'horn' |
| 6. | /patɨ́/ | [patɨ́] | 'name of a fish' |
| | /katɨ̃́/ | [kãtɨ̃́] | 'stinking' |
| 7. | /tatá/ | [tatá] | 'fire' |
| | /hatã́/ | [hãtã́] | 'hard' |

**/k/**

| | | | |
|---|---|---|---|
| 1. | /ʃuká/ | [ʃuká] | 'to show' |
| | /tukã́/ | [tũkã́] | 'toucan' |
| 2. | /pokó/ | [pokó] | 'to touch' |
| | /mokṍ/ | [mõkṍ] | 'to swallow' |
| 3. | /oké/ | [oké] | 'to sleep' |
| | /okẽ́/ | [õkẽ́] | 'door' |
| 4. | /hekó/ | [hekó] | 'custom, behavior' (3 poss.) |
| | /hokẽ́/ | [hõkẽ́] | 'door' (3 poss.) |
| 5. | /ᵈjoká/ | [ᵈʒoká] | 'to break' |
| | /mokã́/ | [mõkã́] | 'to wipe up, wash' |
| 6. | /kaká/ | [kaká] | 'to defecate' |
| | /hakã́/ | [hãkã́] | 'branch' |