

Acoustic Characteristics of Tiwi Coronal Stops

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1. INTRODUCTION

Tiwi is the language of the indigenous people of Bathurst and Melville Islands, located to the north of Darwin in the Northern Territory of Australia (see Figure 1). There are today about 1500 speakers, making this one of the largest communities speaking an Australian language. Like most Australian languages, Tiwi is characterized by a rich set of contrasts among coronal consonants, including four phonetically distinct types of coronal stops. The principal objectives of the present study are to determine what acoustic characteristics distinguish among these coronal stops, and, further, to determine whether there are acoustic characteristics which can consistently be attributed to the distinctive features [anterior] and [apical], which have been used to classify them into two pairs. Secondary goals are to shed light on the articulatory gestures used in Tiwi coronals on the basis of inferences from the acoustic patterns found and through comparison with the work of investigators who have described comparable articulations in other languages on the basis of instrumental data, and to examine certain aspects of the relationship between the acoustics and the articulation of such sounds.



Figure 1. Map of Australia showing location of Bathurst and Melville Islands.

The paper is organized as follows. After brief background sections on Tiwi and coronal-internal oppositions in the world's languages and in Australian languages, probable articulatory properties for each of the Tiwi stop categories will be discussed in the light of work in progress by A. Butcher. These articulatory descriptions will then be related to acoustic characteristics which might accompany them, based on previous work on articulatory-acoustic relations, and a range of specific resulting hypotheses will be described. Next, measurements of durations, burst amplitudes and spectra of Tiwi stop categories will be presented in turn, and discussed, both as they relate to the hypotheses developed, and to the possible articulations of the stops.

1.2. Background

1.2.1 *Tiwi: General background and relevant phonology*

Tiwi is one of the 10% or so of surviving Australian languages which is still being learned by children. However, it has been in contact with English since about 1911, and the language has been undergoing an accelerating process of change in all aspects of its structure, as sentence structures, morphological simplicity and even phonemes are borrowed from English (Lee 1987). The language that will be described and analyzed here is "Traditional Tiwi" (Lee

1987), a stable variant used by those speakers who were over 30 years of age by the mid-1980's.

In the phonological typology for Australian languages used by Dixon (1980), Tiwi is a “single laminal language”; that is, it has three phonemic coronal stops, two of them (alveolar, post-alveolar) regarded as being apical in articulation, and the third (dental) regarded as laminal. Apical stops are made with the tip of the tongue, or its underside; laminal stops are made with the blade of the tongue. Tiwi also has a notably distinct allophone of the laminal stop, conditioned by a following high front vowel. This allophone, described as palatal, has a longer period of frication after the release. There are thus four clearly distinct phonetic types of coronal stops in the language. We will use the symbols /t̪/, /t/, /t̺/, [t̺] for these four types of stops. As we shall note below, all four classes of stops are often contrastive in other Australian languages.

The two published phonologies of Tiwi disagree somewhat on how the four coronal stops are made. Lee (1987) refers to /t̪/ as “laminal dental”, /t/ as “alveolar”, /t̺/ as “post-alveolar”, and [t̺] as “laminal palatal”. Osborne (1974) describes /t̪/ as “apico-dental”, /t/ as “apico-alveolar”, /t̺/ as “apical, slightly above the alveolar ridge” (post-alveolar), and [t̺] as “alveopalatal”. Osborne’s description thus suggests a highly marked situation in which three apical stops contrast in the same language; however, it is possible that by “apico-dental” he is referring to the use of tip and blade together (i.e. a dentalalveolar articulation, see Figure 2 below), or he may simply not be distinguishing between tongue tip and blade. Corresponding nasals exist for the coronal stops. Laterals and rhotics show only two-way distinctions; /l/ vs /ɭ/, and /r/ vs /ɾ/. The overall Tiwi consonant inventory, as interpreted by Maddieson (1984), is shown in Table 1. Note that there is no contrast of voicing among stops nor a fricative series, both also common properties of Australian languages. Lee (1987) largely corroborates Maddieson’s analysis. However, Osborne (1974) and Oates (1967) had considered /t̪/ a combination of /t/ with a preceding postvocalic /ɭ/, reflecting its distributional restrictions to medial position.

Table 1: Tiwi consonant phonemes, after Maddieson (1984).

	Labials	Dentals	Alveolars	Postalveolars	Velars
Stops	p	t̪	t	t̺	k
Nasals	m	n̪	n	n̺	ŋ
Laterals			l	ɭ	
Rhotics			r	ɾ	
Approximants	w			j	y

The three phonemic series of coronals contrast in word-medial position, but in word-initial position apical post-alveolars are absent. As noted above, dentals and palatals are in complementary distribution, with palatals occurring before /i/, and dentals before the other vowels of the language, namely /a, o u/. Words illustrating the Tiwi coronal stops are shown in Table 2.

Table 2: Tiwi words illustrating coronal stops, including allophonic distribution.

	Vowel Environment	Dental/Palatal	Alveolar	Postalveolar
Initial	High front vowel	t̪iraka <i>wallaby</i>	tiwi <i>people</i>	----
	Other vowel (a,o,u)	t̪ampinala <i>cliff</i>	taɲini <i>stick</i>	----
Medial	High front vowel	pikaɲi <i>swordfish</i>	alitiwiyi <i>kangaroo(f)</i>	milikuɲi <i>big toe</i>
	Other vowel (a,o,u)	poɭa <i>bone</i>	kurumuta <i>upper arm</i>	woɭa <i>bush</i>

No stops occur in the coda position of the syllable, including word-final position. There are a limited number of intervocalic consonant clusters consisting of liquids preceding stops. There are also phonetic homorganic nasal + stop sequences which can be viewed either as prenasalized stops, or as an additional series of clusters. We do not know of any evidence in Tiwi that would bear persuasively on this choice. Primary stress is penultimate in Tiwi. In the collected word list there is no marked secondary stress to consider.

1.2.2. Coronal stops in Australian and other languages

Coronal stops are nearly ubiquitous in the world's languages. Of the 452 languages whose phonemic inventories are currently represented in UPSID (Maddieson 1984, Maddieson & Precoda 1992) only Hawaiian lacks a coronal stop. Most languages (81.4% of the sample) have just one distinctive place of articulation for coronal stops. Dart (1991) shows that in languages with one coronal place, actual place of articulation may vary among individual speakers within a given range on the palate as well as on the active articulator. For example, in both English and French, coronal stops are articulated from immediately behind the teeth to just behind the alveolar ridge despite being traditionally described as alveolar in English and dental in French. Similarly, the part of the tongue used varies. In Dart's examination of 20 American English speakers and 21 French speakers, about 78% of the English speakers used an apical articulation, and about 22% used a laminal articulation. The French data was split in the reverse direction (27%, 73%.) Thus, while it is possible to study characteristics common to coronals as a group using languages like English and French, it is not possible to study properties of the apical/laminal or anterior/non-anterior distinctions without direct articulatory verification.

The UPSID corpus includes 67 languages (14.8%) with coronal stops at two distinctive places of articulation, usually apical alveolar and laminal dental (cf. Ladefoged & Maddieson 1986, 1994). Only about 3.5% of languages make use of three or four distinctive coronal stops, and this rare type occurs most commonly in the Australian language family. Of the 3-coronal languages, 10 of 12 are Australian, and of the 4-coronal languages, all are Australian. The usual four-way distinction, regarded as due to the cross-classification of values of the two features, [anterior] and [apical], is as shown in Table 3. Note that if Osborne's (1974) description of Tiwi as having three apicals were correct, it would necessitate the use of an additional feature such as [alveolar], to represent the contrast between two [+apical, +anterior] segments. Table 3 also provides some transcription equivalents in different traditions.

Table 3. Classificatory use of the features [apical] and [anterior].

Feature classification	[-apical] [+anterior]	[+apical] [+anterior]	[+apical] [-anterior]	[-apical] [-anterior]
Possible articulation: Australian convention	"laminal dental"	"apical alveolar"	"apical post- alveolar"	"laminal palatal"
IPA symbol	$\underset{h}{t}$	t	$\underset{h}{t}$	$\underset{h}{t}$
Australianist symbol	th	t	rt	ty
symbol in this paper	$\underset{h}{t}$	t	$\underset{h}{t}$	$\underset{h}{t}$

Despite the general agreement on the phonological classification, previous phonetic descriptions of coronal articulations in Australian languages have shown some variation. It is unclear if this is because the languages differ, or because the descriptions are inconsistent. Jernudd (1974) published palatograms for three male speakers of Gunwinjgu, but no linguographic data. This study showed different ranges of inter-speaker variability for the coronal sounds. More recently, Butcher (in progress) has gathered both static palatographic and linguo-

graphic data and electro-palatographic (EPG) data for one speaker of each of six Australian languages. We summarize the preliminary results below from this work which Professor Andrew Butcher, of Flinders University, Adelaide, has generously made available to UCLA. Although Tiwi is not one of the languages examined by Butcher, the general picture of the articulations found may provide some insight into the likely articulations in Tiwi.

Before we discuss Butcher's results, a brief definitional note is in order. Following Butcher, "tongue tip" will be defined as the point along the rim of the tongue at the midsagittal line, plus 5mm on the dorsal and ventral (sublaminal) sides of the tongue. Variation exists between British and American phonetic tradition in usage of the term "tongue blade". While British tradition (e.g. Catford 1977) defines the blade to include an area 10 to 15 mm back from the rim of the tongue, American (and Australian) tradition defines the blade as a larger area, approximately the front third of the upper surface of the tongue (up to approximately 20 mm back from the "tip".) Keating (1991) argues for the more extensive view of the blade, on the basis that unambiguous (anterior) coronals use this area of the tongue in their articulations. Usage in this paper will follow American and Australian tradition on this point.

1.2.3. Apicals.

Sounds called "apical alveolars" in the Australian languages examined by Butcher are marked by consistency of articulation across both languages and trials. Linguograms and palatograms together show these articulations to be uncontroversially apical and alveolar; the tongue apex makes a narrow band of contact (from 2-7 mm at the midline between the central incisors, measured from photographs of the palate) just at or in front of the alveolar ridge. Little allophonic variation is observed among the articulations. EPG shows evidence of a very rapid closing movement (10-20 milliseconds) and a stable, static hold. (The closing movement is defined as the interval from the time of initial movement of the tongue away from the vowel toward the tectum, until the maximum number of electrode contacts has been reached. But note that the onset of movement away from vowel position is necessarily imprecise because of the nature of EPG records. Only contact patterns are measured, not actual movement.)

Articulations characterized as "apical post-alveolar" show greater variability across the speakers examined, and allophonically within them. Typically, a 5-12 mm band of contact is made in the post-alveolar or prepalatal area, most often sublaminaly. (Butcher also suggests that apical articulations may be characteristic of rapid speech and sublaminal articulations of careful speech.) Postalveolars have slower closing movements than alveolars (30-90 ms) and the hold, once closure has been made, is dynamic; the tongue moves forward so that release is often from an alveolar position. This movement prompts the question of whether postalveolars should be described as flaps. By the criterion used in the TIMIT database (Zue & Seneff 1988) for defining flaps, i.e. lack of release burst, they are not. Moreover, they are much longer in total mean duration (100ms) than the flaps in TIMIT (mean=29ms, Byrd 1993.)

According to Dixon (1980), most Australian languages, like Tiwi, do not display the alveolar/post-alveolar distinction word-initially. Butcher's data shows that the articulation for neutralized initial apicals has characteristics of both the alveolars and post-alveolars in medial position, though they are significantly longer than either in duration. Neutralized apicals are like post-alveolars in that they form a band of constriction in the 5-10 mm range, and move forward between closure and release. On the other hand, they are not usually sublaminal even in careful speech, and are intermediate between the alveolar and post-alveolar categories in their point of constriction on the tectum.

1.2.4. *Laminals.*

Butcher finds that “laminal dentals” involve the dental and alveolar region of the tectum, but may be formed in one of three ways: 1) interdental and tongue-tip up (i.e. the tip is visible between the teeth), 2) interdental and tongue-tip down, (i.e. the tip is behind the lower teeth so that the blade is visible between the teeth) or 3) dentalalveolar and tongue-tip up (i.e. both tip and blade make contact with the surface behind the upper teeth.) The tip-down articulation appears to be least common for the languages examined. Even among the languages with two contrasting laminals, there is a range of variation. Moreover, within a given language all three types of articulation can occur. Variation may in part be attributed to variation in speech style (with interdentals being careful variants, and dentalalveolars rapid variants.) The interdental articulation is easily determined by visual inspection. (Note that the productions of the recorded Tiwi dentals were not interdental, according to the direct observation of the second author.) Whether tip-up or tip-down, “laminal dentals” create a 13-20 mm band at closure, from the teeth to the alveolar zone, so that they are about twice as distributed in the midsagittal plane as apicals.

Articulations described as “laminal palatal” appear to be articulated with the tongue tip down in the majority of cases observed by Butcher, and are similar whether they have phonemic or merely allophonic status. They form a 9-13 mm band of constriction in the alveolar and post-alveolar, or post-alveolar and prepalatal areas. Note that this contact is narrower than for “laminal dentals.” However, additional contact behind the occlusion may be broader at the sides of the tongue, showing evidence of a raised tongue body. An additional factor which probably affects stop durations of “laminal palatals” is indicated by Butcher’s EPG data: at closure, the tongue is initially braced at the teeth, and contact is extended from front to back. At release, contact is “peeled” away, from back to front. (For an account of how bracing facilitates tongue movements, see Stone 1991.) This type of articulation is likely to involve slower movements than those in which the tongue tip meets and pushes off the tectum.

Butcher makes clear that, apart from apical alveolars, there are significant variations in articulation in each of the stop categories, due to idiosyncratic or language-based differences. These aside, Figure 2 broadly summarizes the articulations that Butcher finds representative of the four categories of Australian stop, as drawn by the authors of the present paper. As a point of departure, we will suppose that Tiwi articulations for the coronals stops are as Butcher describes, since we have no reason a priori to expect otherwise.

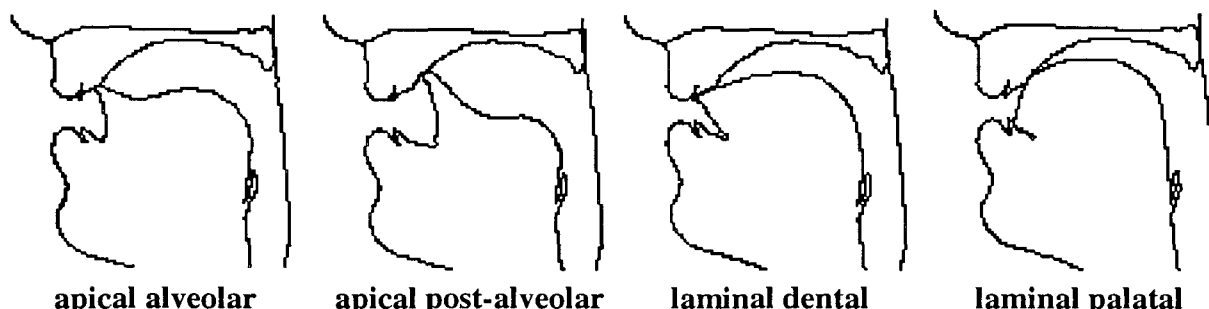


Figure 2. Midsagittal sketches of the articulations of different types of Australian coronal stops, based on descriptions in Butcher (in progress).

2. MATERIALS AND HYPOTHESES

2.1. *Materials*

The experimental materials for this study were collected by the second author during fieldwork at Nguu, Bathurst Island, in 1988, and consist of medium-quality audiotapes of two

female and three male native speakers of Traditional Tiwi. The speakers were in their 50's and 60's at the time that the recordings were made, and represent the most conservative type of speech used in the community. Younger speakers were not used, because, as Lee reports, under influence from English the phonetic realization of the palatal allophone [t] for younger speakers is the affricate [tʃ]. The five speakers will be referred to as B, G, (both female), D, R, and E (male). They were recorded in different groups during three recording sessions in which they repeated selected words in isolation, in response to a prompt in English. Two sessions were recorded indoors, and suffer from some reverberation in the room; the third session was recorded outdoors and is interrupted by bird calls and engine noise. Because of the short time available for constructing a word-list when these recordings were made, and because few minimal pairs exist (Tiwi words are often three to five syllables in length) materials are imperfectly balanced for vowel environment, length and other factors. Moreover, for a variety of reasons the speakers provided between six and zero tokens of each word (normally about two). These factors limit the extent to which some desirable comparisons can be made in a controlled way.

In the discussion of results below, relative duration, relative amplitude, and shape of the burst spectrum will each be considered in a separate section. The allophonic palatal will be treated as a separate category so as to show its characteristics in these domains.

2.2. Hypotheses

Two kinds of hypotheses will be entertained, focussing either on the characteristics of individual stop places of articulation or on acoustic characteristics attributable to their component features. We do not expect that duration components, relative amplitudes and spectral properties, each taken alone, will distinguish the four categories. But we have every reason to believe that some combination of duration, relative amplitude and spectral properties taken together, will reliably distinguish all four stops. We will call this general idea Hypothesis 1.

Our other hypotheses focus on acoustic properties that might be associated with the feature opposition [+anterior] (at or in front of the middle of the alveolar ridge) and [-anterior] (behind the middle of the alveolar ridge), or the feature opposition [+apical] and [-apical]. We hypothesize that acoustic bases for the groupings of [+apical] consonants, [-apical] consonants, [+anterior] consonants and [-anterior] consonants can be found. In testing for such groupings, the following specific hypotheses will be considered. Hypothesis 2: A stop's value for the feature [anterior] will affect durations of stop closure. [-Anterior] articulations will show shorter closures than [+anterior] articulations. Hypothesis 3: A stop's value for the feature [apical] will affect durations of stop release. Laminals ([-apical]) will have longer release durations than apicals. Hypothesis 4: Laminar stop bursts will have lower amplitudes than apical stop bursts. Hypothesis 5: The [-anterior] stop categories will be characterized by burst spectra which have high amplitude energy concentrated in a narrow frequency range, whereas [+anterior] stops will show a wider distribution of high amplitude energy.

2.2.1. Acoustic background to hypotheses: Duration

It has often been said that the further back the place of articulation is for a stop, the shorter the closure duration, and the longer the VOT. Thus, investigators have usually found that labials have longer closures than velars (Fischer-Jørgensen 1964, Zue 1976, Keating 1984a) and that VOT is shorter for labials than velars (Fischer-Jørgensen 1954, Keating, Westbury & Stevens 1980, Crystal & House 1988.) Often, provided the effects of language-specific processes such as the American English "flapping" of coronals are set aside, coronal stops show intermediate durations between labials and velars (Stathopoulos & Weismer 1983, Ren 1985). If "backness in the mouth" influences durations, we might expect anterior coronals to have longer

closure closure and shorter release than non-anterior coronals. However, on further analysis such a conclusion is not so clear. Explanations of closure differences have focused on the fact that intraoral pressure reaches a peak value more quickly when the supraglottal cavity behind the constriction is small than when it is large. VOT differences are thought to depend on the speed of articulatory release. The tongue tip moves fast, but the slow-moving tongue body means that it takes longer to reinstate a pressure differential and begin voicing in velars. Since the lips are more elastic than the tectum, more compression is likely during labial holds than tongue/tectum holds (also yielding longer durations), but the elastic rebound from this compression contributes to a fast release for labials. For these several reasons, a front-to-back ordering often obtain for closure and release of labials, coronals and velars, but we cannot necessarily expect this to hold for coronal-internal comparisons. Place of articulation *per se* is not important; what do seem to be important are wall area behind the constriction (which in coronals is influenced by the tongue shape as a whole, not just point of constriction) and mass of the active articulator.

If articulator mass influences stop component durations, we might expect the tongue blade to move more slowly than the smaller, lighter tongue tip in reaching the tectum, in forming a wide seal, and in breaking that wide contact. (This seems especially likely for palatals, in light of Butcher's observations indicating that the tongue first anchors itself on the tectum and then rolls back and forward again while closure is maintained.) Thus, in relation to the surface area of the tongue making tectal contact, [-apical] seems to imply a greater duration of closure. However, another factor is involved in the [apical] distinction. Svarny and Zvelebil's (1955) x-ray data shows that Tamil laminals involve higher jaw positions for their articulations than apicals. On this basis, holding [anterior] constant for paired comparisons, we would expect dentals to have briefer closures than alveolars, and palatals to have briefer closures than post-alveolars, because their higher jaw positions would entail smaller supraglottal cavity volumes. These potentially opposing effects of articulator mass and jaw height make it difficult to predict how apicality will affect closure duration overall. Thus a hypothesis based on [apical] (Hypothesis 3 above) could predict longer durations of release for [-apicals], but not relative durations of closure.

2.2.2. *Acoustic background to hypotheses: Voicing*

Weismer (1980) found a constant duration of the voiceless portion (closure plus release, or VOT) for the English voiceless stops /p, t, k/ regardless of place of articulation. He interpreted this as due to the presence of a consistent glottal opening (devoicing) gesture, whose time course is uninfluenced by place. While total voiceless duration remained constant, the ratios of voiceless closure to voiceless release identified place of articulation. If Tiwi also incorporates a glottal opening gesture during stops, such ratios would be an important aspect of duration to consider. Tiwi stops are described by both Osborne (1974) and Lee (1987) as generally voiceless and unaspirated. However, since voicing is not distinctive in Tiwi, it may be premature to assume that a glottal opening gesture is involved in producing these stops.

2.2.3. *Acoustic background to hypotheses: Spectral shapes of stop bursts*

Stop places have also been identified on the basis of the spectral pattern of the stop burst. Adapting acoustic featural descriptions proposed by Jakobson, Fant and Halle (1952), Blumstein and Stevens (1979) found 85% identifiability of the spectra of labials as diffuse-falling, alveolars as diffuse-rising and velars as compact. "Falling" (or "grave") denotes a downward-tilting slope on a line drawn from peak to peak and "rising" (or "acute") denotes an upward slope on a spectrum calculated using a 25.6 ms half-window beginning at stop release (thus including frication), and a frequency range of 0 to 5 kHz.

Lahiri, Gwirth & Blumstein (1984) later used this metric to attempt to group the

contrasting dentals and alveolars of Malayalam together, and find unifying characteristics of coronals as opposed to labials. Only 71% of alveolars fit into the diffuse-rising template, and only 57% of dentals did. We infer from this, and from the illustrations they provide, that the spectra of Malayalam alveolars and dentals were fairly different from each other. (Lahiri, et al (1984) and Keating and Lahiri (1993) also examined the relation of burst spectra to the spectra of following vowels, but hypotheses based on these studies will not be addressed here.) Dart (1991), examining contrasting apicals and laminals in Malayalam and 'O'dham, found trends toward flat spectra for dentals, rising spectra for palatals, a low-frequency energy peak for retroflexes (both sublaminal and apical) and more highly peaked spectra for alveolars than dentals. (She focused a very short FFT window over the burst, so as to exclude frication from the spectrum.) These results, too, indicate that contrastive coronals can show different spectral signatures. Fant (1960) ascribes spectral differences among stops to differences in the cavity in front of the occlusion; burst spectra can therefore give us an acoustic "picture" of the space in front of a stop constriction. There is reason to believe that the four Tiwi stop categories involve front cavities of sufficiently different shapes that their spectra will differ appreciably. This is encouraging in terms of Hypothesis 1, but can we relate these differences to features?

Stevens and Keyser (1989) note that [-anterior] articulations cause a major peak in the midfrequency range, because of the high ratio of the length of the front cavity to the length of the back cavity. For these articulations, either F2 and F3, or F3 and F4 are closely approximated, combining to form one peak. However, they suggest that [-anterior] will only be strongly salient in [-sonorant] [-coronal] segments, since the high frequency energy present in [+coronal] spectra will mask the midfrequency peak caused by the front cavity. In light of Lahiri et al. and Dart's findings that [+coronal] spectra can instead be diffuse-flat, we hypothesize that the Tiwi [-anterior] stops will contain an isolated (therefore potentially salient) midfrequency peak (Hypothesis 5).

2.1.3. Acoustic background to hypotheses: Burst amplitude.

Keating, Westbury & Stevens (1980) show that English voiceless alveolar stops have an early amplitude peak after release of closure, followed by a sharp drop-off of noise, while velars show much later peaks of energy following release, and gradual dissipation of noise. Release energy for distributed stops like velars is diffused over a relatively long period following the break of closure, while the energy of a less distributed stop is dissipated in a much shorter length of time. Extrapolating to coronals, we expect the burst energy of apicals to be of greater amplitude and to be contained in a shorter period than in laminals. Jongman, Blumstein & Lahiri (1985) found this result in Malayalam. At the burst release, Malayalam apical alveolar stops were reliably higher in amplitude than laminal dentals (articulations are confirmed by Dart, 1991). We project similar differences for Tiwi apicals and laminals (Hypothesis 4.) Note that quieter bursts and longer VOTs for laminals are attributed to the same cause: slow movement of the articulator prolongs obstruction of the supraglottal cavity, and prevents a rapid escape of air.

3. DURATION MEASUREMENTS

3.1. Data and methods

The Kay Elemetrics Computer Speech Laboratory (CSL) was used to digitize and measure portions of words containing coronal stops in various vowel and stress environments. Only stops in intervocalic or initial environments were considered; coronals in consonant clusters were excluded. For the examination of duration, all words of the specified form were measured so as to balance out effects of different factors over the largest available sample. The 38 words measured are listed in the Appendix. For some analyses, subsets of the data were used in order to isolate certain effects from potentially confounding factors. Selected examples isolating

vowel environment, stress environment and position in word are shown in Table 4 (a-c).

Table 4. Subsets of words used to isolate particular factors in the duration analysis. The syllable in question is shown in **boldface**.

(a). Vowel environment.

	Following Vowel ---->			
Preceding Vowel ↓	i	a	o	u
i	alitiwiyi <i>kangaroo (f)</i>	kitatawini <i>bread</i>	----	----
a	yati <i>one</i>	tiŋata <i>beach</i>	----	paŋipaŋuwu <i>turtle egg</i>
o	----	poŋa <i>bone</i>	----	----
u	kumuŋi <i>beard</i>	kurumuŋa <i>upper arm</i>	----	tuŋutuŋi <i>move around</i>

(b). Stress. (Primary stress is penultimate).

Stress Environment	Tiwi exemplar (vowel environment constant)	English Gloss
pre-stress	alitiwiyi	<i>kangaroo (f)</i>
stress	muritiwa	<i>neck</i>
post-stress	poaliti	<i>beard</i>

(c). Position in word.

Position in Word	Tiwi exemplar (vowel environment and stress constant)	English Gloss
initial	ŋampinaŋa	<i>cliff</i>
medial	kitatawini	<i>bread</i>
final	piraŋa	<i>rice</i>

2.1.2. Duration measurements

Because there is some evidence that salient frequency information for obstruents can be contained in frequencies as high as 12 or 16 kHz (Sands 1991 for clicks), material was initially sampled at 40 kHz, to make use of this range. However, a consistent band of noise on the recordings between 8 and 11 kHz meant that analysis had to be limited to information below 8 kHz, and waveforms were subsequently downsampled to 20 kHz to maximize resolution of information in the 0 to 8 kHz range.

Duration measurements were made using simultaneously displayed, time-aligned waveform and amplitude windows, and two spectrogram windows. Time-cursors can be linked across all four windows so that events and times can be reliably matched. An example of the four time-aligned windows is shown in Figure 3. A very wideband (586 Hz) spectrogram was displayed (lower left) in order to obtain fine resolution of the time axis. This made possible a reliable determination of the points at which stop bursts and voicing occurred. A 293 Hz bandwidth spectrogram (lower right) resolved formants. In some cases the energy display facilitated determination of onset or offset of voicing, as well as the position of the burst. Duration measurements for VTV sequences (where T = any coronal stop) were divided into six increments, as shown in Figure 4.

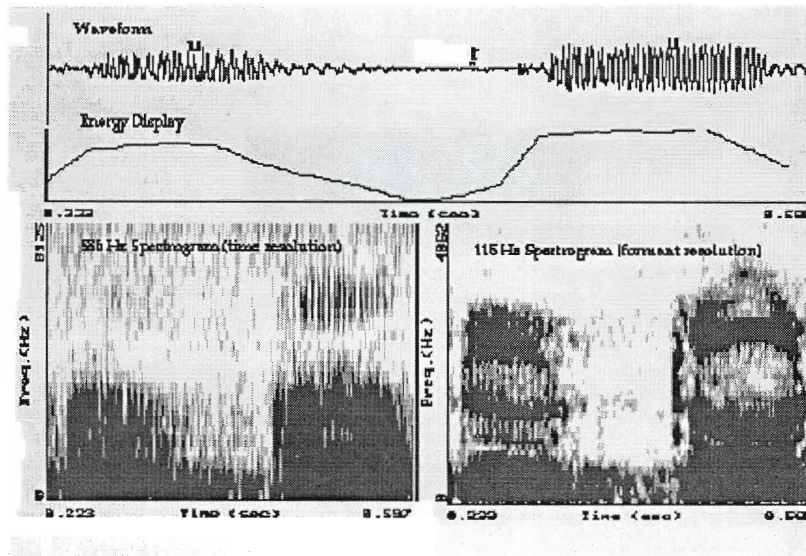


Figure 3. Example of display used for measuring duration on CSL.

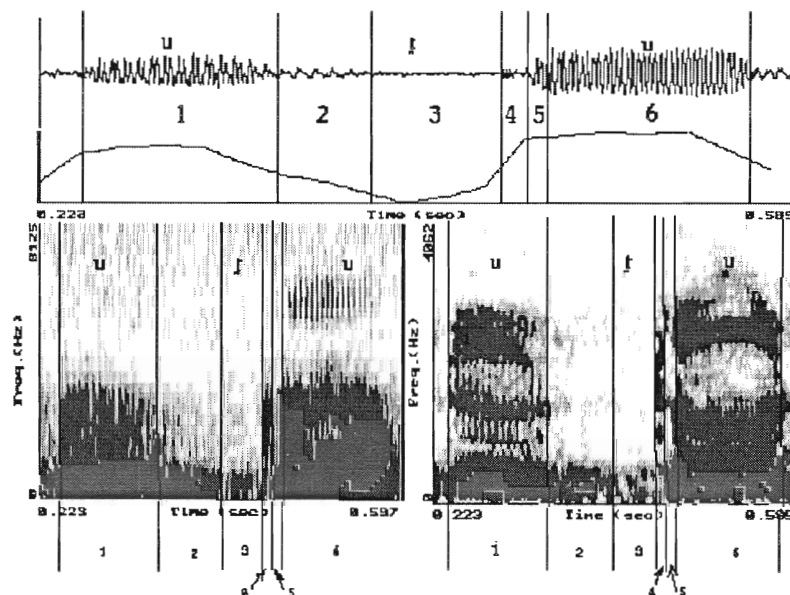


Figure 4. Increments used in measuring durations of Tiwi VTV intervals

Increment 1 is the duration of the vowel preceding the stop in question, from onset to offset of visible formants. Increment 2 includes just the voiced portion of the stop closure, from the point at which the higher formants of the preceding vowel disappear, to the end of visible voicing. The third measure contains the voiceless, silent portion of the closure. Voiced and voiceless portions of stop duration were measured separately in order to determine whether degree of voicing plays any role in differentiating these stop categories. We also entertained the idea that obstruent voicing in a language with no phonemic voicing distinction may be in completely free variation, or may be a matter of the speaker's preference. (Note that these first three measures are not applicable to initial stops.) The fourth section measures the time from the beginning of the transient indicating release of tongue contact with the roof of the mouth, to the onset of vibrations of the vocal folds. This is voice onset time (VOT), as traditionally

understood (Lisker & Abramson 1964.) The fifth component is the voiced section of the release. This measurement consists of the period during which the vocal folds have begun vibrating, but frication noise is still apparent on the spectrogram. Increment 6 is the duration of the vowel following the stop in question, once again from onset to offset of formants. In some cases one or more of these increments had values of zero.

This data was not normalized for speech rate variation within speakers. First, there was no carrier phrase with which to compare speech rate over multiple utterances. Normalization of consonants with respect to their syllables was considered, but was rejected because of the unbalanced nature of the data set. As mentioned earlier, several factors which potentially affect duration varied across tokens. Syllables of interest appeared in various stress environments, various vowel environments, and various positions in the word. In addition, the number of syllables in a given word, which also affects syllable durations (Lehiste 1970), varied across tokens. A 3-factor analysis of variance (ANOVA) for stop category, speaker and position in word showed a very significant statistical effect of position in word on duration of syllables. Penultimate syllables were greatest in length because they were always stressed, followed by word-final syllables (which are subject to prepausal lengthening, Klatt 1975.) Syllables in antepenultimate or earlier positions were shortest in duration. To balance for each of these factors would have yielded excessively small subsets of words. Moreover, if durations of neighboring vowels affect consonant identification, we would want to catalog this variation, rather than removing it from consideration by using it as a normalizing tool.

However, to screen the data for gross variations of speech rate, the median was calculated for each speaker for all VTV intervals measured (for TV in the cases of consonants in initial position, and GVTV sequences). Total VTV (or TV) interval was considered the best index of speech rate among the measures taken. Assuming that duration differences arising from gross variation in speech rate would be of a much greater order than those contributed by factors like stress, intrinsic vowel duration and word position, tokens whose measurements fell more than two standard deviations away from speaker medians were considered outliers for speech rate and excluded.

3.2. Results

Unless otherwise noted, each of the ANOVAs mentioned below is a 2-factor analysis, with stop category and speaker identity being the two factors. Speaker identity was included so as to account for a significant probable source of variance; this factor in every case turned out to be significant. Interaction terms between the factors will not be mentioned unless statistically significant. For post-hoc comparisons between means, Fisher's Protected Least Significant Difference (PLSD), corrected in this statistics package for unbalanced data sets, is used.

3.2.1. Duration of word-initial vs intervocalic consonants

As mentioned above, Butcher found initial apicals to be longer in duration than intervocalic ones. To determine whether initial and intervocalic stops showed different durations for Tiwi, a 3-factor ANOVA was performed with stop category, speaker identity, and initial or intervocalic position as main effects. Only release durations can be compared in our data, as the onset of closure cannot be determined in the initial stops. The result is shown in Figure 5; in this and following figures showing data in histogram form the error bars show one standard deviation (95% confidence level). Initial stops are significantly longer in total release duration than intervocalic tokens for the three categories compared (post-alveolars were excluded from consideration, as they do not occur in initial position), but the order of categories remains the same. Since a significant effect was found for initial vs intervocalic position, each of the tests

below which included initial consonants was performed separately for combined initial and intervocalic data and for just intervocalic (VTV) data. No significant differences in the patterns of results were found, so the more inclusive result is reported.

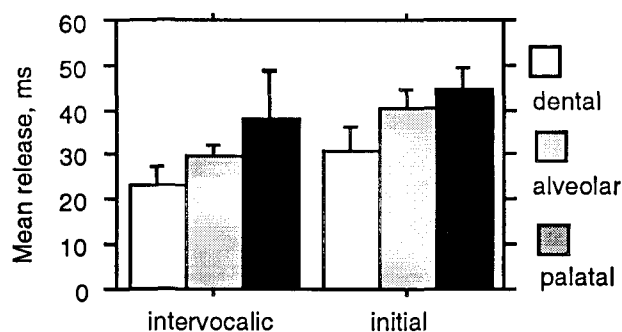


Figure 5. Mean release durations of inter-vocalic vs initial stops, by coronal stop category.

3.2.2. Duration of closure

Mean values for the total closure duration of four stop categories are shown in Figure 6. Total closure is the sum of both voiced and voiceless sections of stop closure, from disappearance of formants of a preceding vowel to the moment of the stop burst. Although the main effect of category on closure duration was highly significant ($F[3, 313]=8.180, p<.0001$), only the post-alveolar category is significantly different from each of the others in post-hoc comparisons of means. Other categories could not be statistically distinguished. Thus the main result is that post-alveolars are shorter in closure duration than the other categories. Dentals and palatals also tend to have slightly larger standard deviations than alveolars and post-alveolars (a trend which will continue in most of the tests below), reflecting greater articulatory variation.

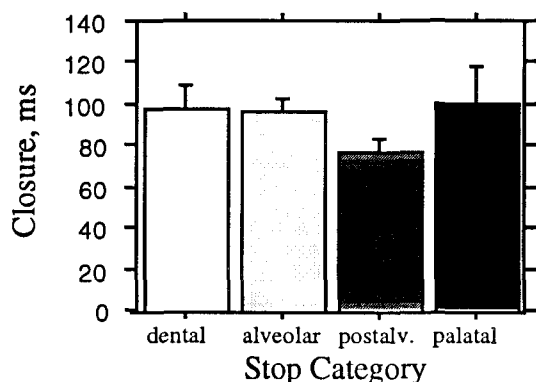


Figure 6. Mean total closure durations for Tiwi consonant types.

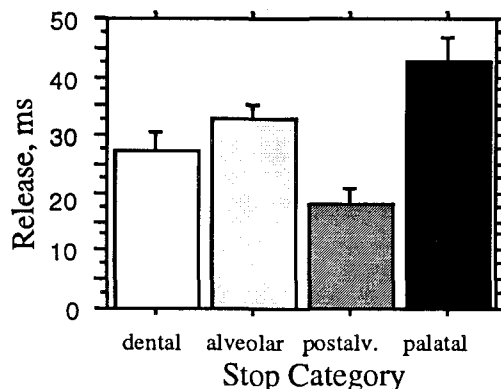


Figure 7. Mean release durations for Tiwi consonant types.

3.2.3. Duration of release

Total release refers to the duration of the stop from its burst to the onset of formants for the following vowel, and so includes VOT as well as any short voiced portion which reflected the presence of a consonantal constriction. Mean durations of releases for the four coronal stops

are shown in Figure 7. Post-alveolars had the shortest mean durations of release, followed by dentals, alveolars and palatals. ANOVA showed a very significant effect of stop category on release duration ($F[3, 448]=40.89, p<.0001$), and in this case each pairwise comparison between categories was statistically differentiable from the others.

3.2.4. Durations of voiced and voiceless components of stops

Mean durations of the voiced portion at the onset of intervocalic coronal stop closures are shown in Figure 8. Duration of voiced closure does not distinguish stop categories ($p=.9607$). Values are very similar for all four stops types; voicing persists during 45-50 ms of the closure. These numbers are in the range of Keating's (1894b, 1984c) results modeling passive devoicing of voiced stops, such as English /d/, and suggest that Tiwi stops are not produced with an accompanying glottal opening gesture. Rather, voicing may cease due to passive factors such as the equalization of supraglottal and subglottal pressure. The lack of a glottal opening gesture means that the ratio of voiceless closure to voiceless release is not an appropriate metric for distinguishing Tiwi stops.

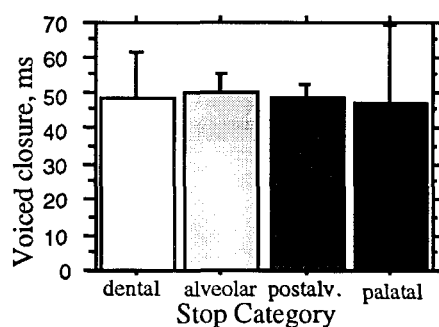


Figure 8. Mean durations of voiced portions of Tiwi stop closures, by category.

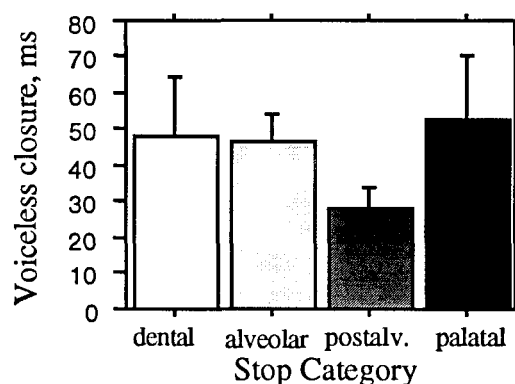


Figure 9. Mean durations of voiceless portions of Tiwi stop closures, by category.

Mean durations of the voiceless portion of intervocalic coronal stop closures are shown in Figure 9. Post-alveolars are significantly different in pairwise comparisons from every other group, but none of the other categories was significantly distinguishable. Note the similar pattern in Figure 9 and Figure 6, which shows total closure duration. Clearly the voiceless portion of closure contributes most of the differences in closure among the stop groups.

Mean durations of the voiceless portion (VOT) of the stop releases are shown in Figure 10. All of the stop categories were significantly differentiable from each other, except for the dental and alveolar categories. Dentals and palatals showed higher standard deviations than alveolars and post-alveolars. Among individual speakers, VOTs for post-alveolars and palatals always stood in the same relation — palatals showing the longest VOTs and post-alveolars the shortest. But the relationship between dental and alveolar categories depended on the speaker. As shown in Figure 11, Speaker G has considerably longer VOT for alveolars than the other speakers, and a substantial difference between alveolar and dental values. The other four speakers have more equal VOT's for alveolars and dentals. Comparison of Figure 10 with Figure 7 above shows that VOT forms the major contribution to total release duration, as compared with voiced release, for which results are shown in Figure 12.

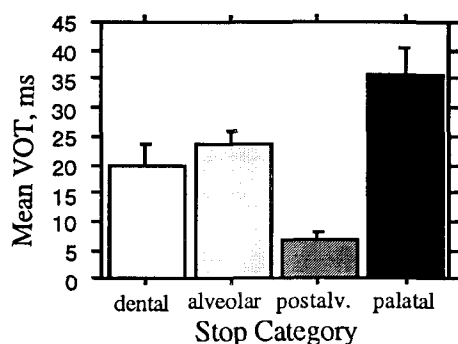


Figure 10. Mean VOT durations for Tiwi stop categories.

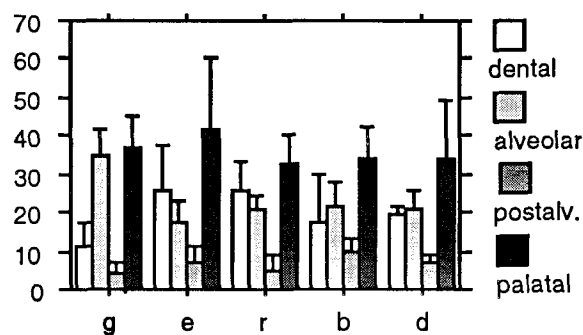


Figure 11. Individual speaker means of VOT for each consonant type.

Mean durations of the voiced release component of stops are shown in Figure 12. (Recall that this is the portion at the onset of the post-consonantal vowel where voicing has started but where signs of the effect of the consonantal constriction, such as some residual frication, are still apparent. Not all stops displayed such a portion and demarcation of this interval was sometimes problematical.) The post-alveolar category was significantly different from the dental and palatal categories. None of the other pairs of comparisons yielded a statistically reliable difference.. Some trade-off between components of release duration is thus apparent, as the post-alveolar VOT is significantly shorter than those of dentals and palatals. Note that while neither VOT nor voiced release duration alone separates dentals from alveolars, the total release duration for alveolars is significantly longer than that for dentals (Figure 7.)

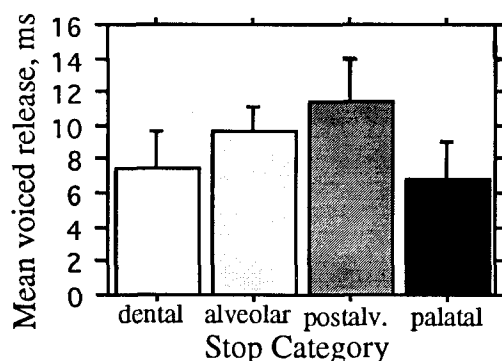


Figure 12. Mean voiced release durations for Tiwi stop categories.

3.2.5. Durations of surrounding vowels

Fischer-Jørgensen (1964) found that, for Danish, place of articulation distinctions can be reflected in the relative durations of a preceding vowel. To test for the possibility that differences in vowel duration signal a stop's identity to Tiwi speakers, the durations of both preceding and following vowels were analyzed.

An ANOVA testing the effect of stop category (and speaker identity) on the duration of the vowel preceding the coronal in question showed no significant differences. However, the effect on the following vowel (V2) was highly significant. In this case the ANOVA for vowel durations included the position of the syllable in the word as a factor, as well as preceding stop category and speaker identity. Speaker identity was marginally significant ($p=.0423$), reflecting

some difference in characteristic speaking rates, while both stop category and position in word were highly significant ($p < .0001$). (For position in word, stressed syllables are longest, followed by word-final syllables. Syllables falling before the penultimate syllable are shortest.)

The mean durations of V2 after each coronal stop category are shown in Figure 13, together with the total release duration, yielding the total syllable duration (TV). The longest duration for V2 is after post-alveolars, the shortest after palatals, and the dental category shows a longer mean V2 than alveolars. The V2 duration of each of the pairs was distinguishable at a $p < .0001$ level, excepting dental vs alveolar and dental vs post-alveolar, which were not significantly distinct. More important, however, is the trend of inverse relationships we see between release duration of the stop, and duration of V2. Recall that for total release, post-alveolars are shortest, and palatals longest, with alveolars showing longer mean release durations than dentals (Figure 7.) Because of this trade-off between release duration and following vowel duration, TV duration across categories is very nearly constant. The apparent exception to this constant syllable duration are syllables with palatal onsets, which remain shorter than the others.

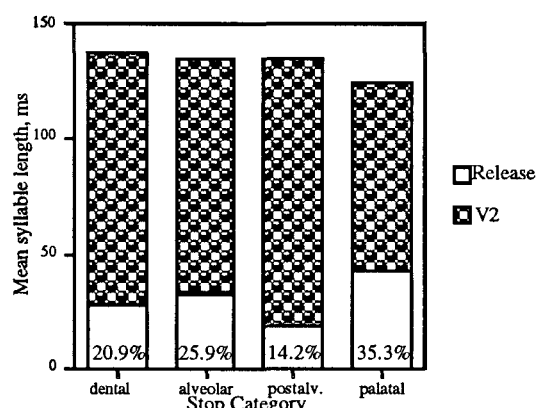


Figure 13. Mean TV syllable lengths, by proportions of release and V2

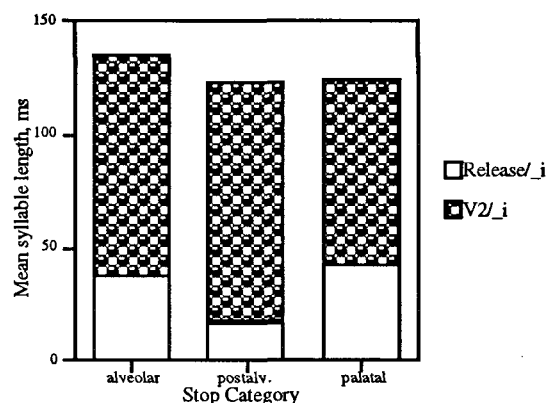


Figure 14. Mean lengths of /Ti/ syllables

However, recall that palatals only precede /i/; this short syllable duration was suspected to be a result of the short intrinsic duration of /i/. Figure 14 shows relative contributions to syllable durations of stop release and following vowel for just the /i/ environment (which excludes dentals.) Here, although alveolars and post-alveolars show an unexpected significant difference, palatals fall between them, and are indistinguishable from either group. Thus, when intrinsic vowel length is controlled for, syllables containing palatals are not significantly different from other categories of stop.

3.3. Summary and discussion of durations

The general pattern seen in the duration results is that while the apical post-alveolars and the laminal palatals can often be clearly distinguished in pairwise comparisons, the post-alveolars are not typically grouped together with the apical alveolars, nor are the palatals typically grouped with the dentals. Where there is no significant difference between the two apicals or the two laminals, it is often the case that three or four of the coronal stop categories do not differ. There is even less evidence for a grouping of the two [+anterior] place categories, or the two [-anterior] categories. Clearly, there is no direct relationship between the classificatory features [anterior] and [apical] and any particular durational component. Rather, the evidence points to an

intermediate level of phonetic parameters (Keating 1988). The features [anterior] and [apical] interact to determine a general oral tract shape and size. They may work “cooperatively” or “antagonistically” in creating an overall oral tract configuration. For example, [-apical] and [-anterior] values both contribute to a small oral cavity, but whereas [+anterior] suggests a larger oral cavity behind the closure, an articulation simultaneously specified for [-apical] will probably involve a raised tongue and jaw, which work to decrease the size of the oral cavity. It is this overall oral tract configuration, as well as an articulator’s speed of movement and specification for movement during the articulation (as for the post-alveolar), that predict more closely the resulting acoustics. Neither [anterior] nor [apical] can predict the acoustics of duration without referring to effects of the other feature. The kind of complex relationship assumed can be summarized by the schema in Figure 15.

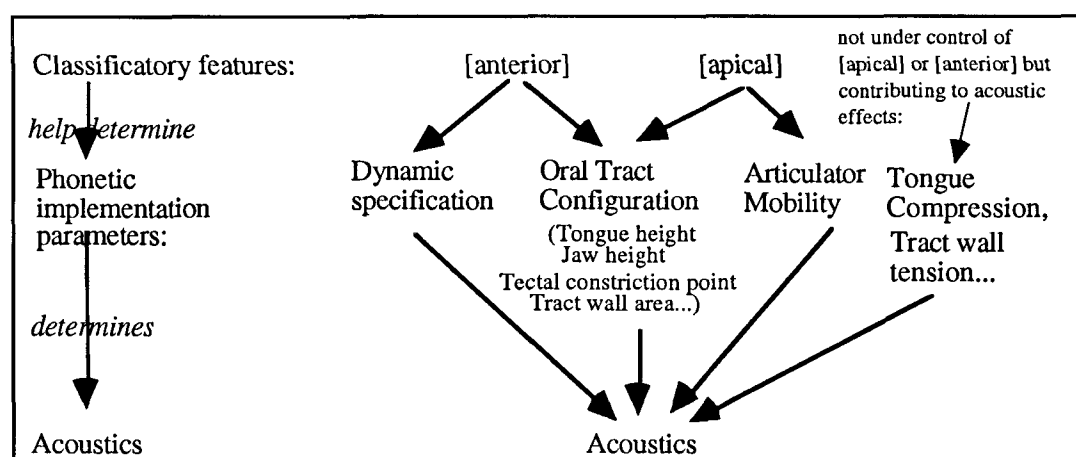


Figure 15. Schematic representation of the suggested relation between [anterior] and [apical], the phonetic implementation component, and acoustic output.

Let us review the duration results in light of the specific hypotheses concerning duration outlined above. Hypotheses 2 and 3 respectively predicted longer closure durations for anterior coronals than for non-anterior coronals, and longer release durations for laminal coronals than for apicals. Since mean total closure was very similar for three of the stop categories (Figure 6), Hypothesis 2 fails. However, it fails only for palatals, correctly predicting long closures for dentals and alveolars, and short closure for post-alveolars. The unexpected length of the palatal closure may be related to the time required to make a rolling movement of the tongue similar to that indicated by Butcher’s data. This particular type of dynamic specification may over-ride the relationship between anteriority and closure duration. A possible effect of anteriority on relative offset of voicing after closure was also anticipated, but was not observed (Figure 8).

Hypothesis 3 correctly predicts a short release for post-alveolars and a long one for palatals. It fails, however, in differentiating dentals from alveolars, which are similar in release duration and intermediate between the post-alveolar and palatal categories. In this case, it seems that more specific characteristics of the stops than their classification in terms of [apical] may be responsible for the apparent partial success of the hypothesis. While the low mass of the tongue tip probably facilitates a quick release for apical post-alveolars, early onset of voicing may be most effectively enhanced by a forward movement of the tongue during the closure of these stops, expanding the supraglottal cavity so that the pressure differential required for voicing is reached quickly. Recall that the ‘voiced release’ portion was longest for post-alveolars, indicating that voicing starts at an early point in the release movement while the aperture is still somewhat constricted (Figure 12). For the palatals there is a long (‘distributed’) constriction of

(tip and) blade behind the alveolar ridge, and probably a higher jaw and higher tongue body position behind the occlusion. We assume the supraglottal cavity is the smallest of all the coronal types, and the rolling pattern of closure formation from front-to-back actually reduces the cavity size during the first part of the closure. Breaking this contact and re-establishing conditions for voicing takes longer under these conditions.

Alveolars have longer VOTs than post-alveolars, probably because they are static during closure; they do not benefit from the decrease in pressure afforded by a forward movement of the articulation during closure. Alveolars are shorter in VOT than palatals due to the light mass and greater mobility of their articulator, and the probable lack of narrowing of the oral tract behind the constriction. The reason for the similar release durations of dentals and alveolars is not clear. As Tiwi has no aspiration or voicing contrasts, we posit that the patterns of release and V2 durations in coronal stops are due to biomechanically and aerodynamically determined effects. Thus, the constant TV syllable length reflects the fact that the same articulatory gestures are used for the vowel regardless of the preceding consonant. The proportion of the syllable counted acoustically as part of the release is dependent on where non-fricated, high-amplitude voicing can begin, as determined by considerations of supraglottal volume, rate of aperture increase, etc. These considerations must balance out in the case of the two anterior coronals.

The duration results for Tiwi generally parallel results from other languages in which multiple coronals articulations have been examined, and in which the articulatory gestures used have been studied by palatographic techniques. The Tiwi post-alveolars stand out as shorter in duration than each of the other categories in most tests. Short durations have also been found for Malayalam sublaminal and apical post-alveolars (Dart 1991) and Toda sublaminal post-alveolars (Shalev, Ladefoged & Bhaskararao 1993). Tiwi palatals are distinguished from other categories by long VOT. Malayalam laminal alveolars and 'O'odham laminal or apicolaminal alveolars are also distinguished by long VOT (Dart 1991).

The difficulties in differentiating Tiwi dentals and alveolars by duration are not isolated. Dart (1991) found no differences in closure duration between dentals and alveolars in both Malayalam or 'O'odham, and longer VOT (for the laminal interdental) in the case of only one of three speakers of Malayalam. The speakers who used laminal dentalveolars did not have significantly different VOT's. In Toda, VOT does not distinguish laminal dentalveolars from apical alveolars (Shalev et al. 1993.) In Dahalo, it is the (confirmed) apical alveolars that have very significantly longer VOTs than laminal dentals! (Maddieson, Spajić, Sands & Ladefoged 1993). One possible explanation for the Dahalo case, noted by the authors, is that placing frication on the alveolar is an active gesture designed to distinguish it sufficiently from the dental. In Iaa (Maddieson & Anderson, forthcoming), it is post-alveolars which have longer periods of frication than dentals, which adds weight to the idea of frication as a potential active enhancing characteristic with which to separate coronal categories. Tiwi does not choose this option, however.

4. RELATIVE AMPLITUDE

4.1. Procedure

4.1.1. Data

For examinations of relative amplitude and spectral shape, subsets of words were chosen for the purpose of comparing stop categories in nearly balanced environments. Recall that the data set as a whole was unbalanced in several respects. Not every speaker produced every token in the word list, numbers of repetitions of tokens varied among speakers, and vowel and stress environments, and position in words, were not equally matched across stop categories. The

subset of words shown in Table 6 was chosen for the examination of relative amplitude. Where more than one word occurs in a cell this is because insufficient tokens were available of a single item but a well-matched substitute word was available. Wherever possible, at least two tokens of each stop in each environment were obtained for each speaker. Because a larger data set was available for coronal stops in unstressed syllables, stops in stressed (penultimate) syllables were avoided. Analyses also considered whether the stop fell in an initial, medial or final syllable.

Table 6: Data subset used for relative amplitude study. Numbers of tokens measured are shown after each word. For clarity, glosses are not included here, but can be found in the Appendix.

	Vowel Environment	alveolar	post-alveolar	dental	palatal
Initial stops	#_a	tarīṇa (7) tarīṇi (5)	--	ṭampināḷa (10)	
	#_i	tiṇata(9) tinimūli(2)	--		ṭitāka (4) ṭirāka (7)
	#_o	tokampīni(4) tokampūṇa (3) toṇulāka(3)	--	--	
	#_u		--	ṭukwantāṇa (5)	
Intervocalic stops	a_i	yāti (12)	pulaṭi (11)		pikaṭi (10) paṭipaṭuwu (2)
	a_a	tiṇata(10)	kitaṭawini (9)	piraṭa (10)	
	u_a	kurumuta (9)			
	o_a		wōṭa (7) values for 4/5 speakers	pōṭa (8)	

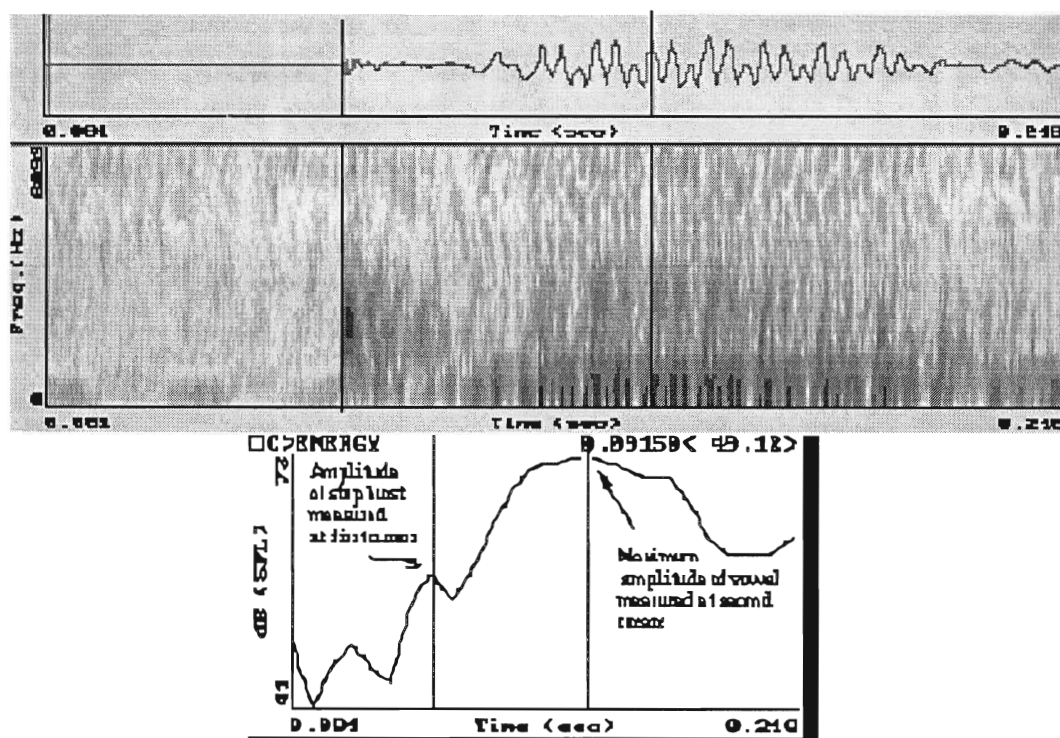


Figure 16. Time-aligned CSL windows used for measuring relative amplitude of stop bursts from waveforms

For each token, energy measurements were taken on CSL of the peak amplitude of the burst transient for the consonant in question, and of the maximum amplitude of the tautosyllabic vowel. As in the duration portion of the study, simultaneously displayed and time-linked waveform, spectrogram and energy windows facilitated finding locations of burst transients and vowel maxima. Figure 16 illustrates the display used. Amplitude information for the energy display was averaged over short unsmoothed windows of 10 ms with time advances through the displayed data at 5 ms intervals, to capture small increments or decrements in energy. In most cases the burst peak was prominent enough to be unambiguous in each of the displays, and the local maximum amplitude which most nearly corresponded to the location of the burst peak on the waveform was recorded. In ambiguous cases in which a ramping effect from burst to vowel was observed, the value at the moment of the burst (on the waveform) was recorded. For vowels, the maximum energy displayed by the amplitude window was recorded.

4.1.2. Analysis and interpretation of data

In the discussion below, the decibel (dB) values reported are not the raw measures taken from bursts, as in the diagram above, but rather differences between the peak amplitudes at tautosyllabic vowel maxima, and peak amplitudes at burst transients. This derived measure was employed as a way to normalize for a speaker's amplitude; it better reflects the energy of the burst compared with the overall amplitude for a given utterance. This idea, based on Jongman, et al. (1985) departs from their procedure in using differences in dB between vowel and burst amplitude, rather than vowel amplitudes divided by burst amplitudes. We feel this procedure reduces the effect of outliers.

Note that because amplitude differences between vowel and stop burst are used, rather than raw values for bursts alone, a large value for "vowel minus burst" (hereafter "vowel-burst") for a given token means either a low-amplitude burst, a high-amplitude vowel, or a combination of these two conditions. Alternate possibilities are illustrated in Figure 17.

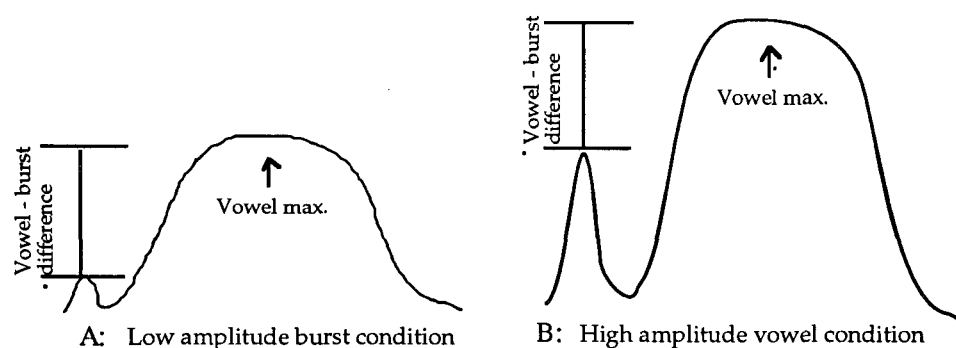


Figure 17. Two scenarios yielding a large difference in "vowel-burst" amplitudes.

On the other hand, a small difference in vowel-burst amplitude means either a high-amplitude burst with respect to the following vowel, or a low-amplitude vowel (or again a combination of these factors). This is illustrated in Figure 18. Since both amplitudes being measured may vary independently, it is important to make comparisons between stop categories in well-matched subsets of data, e.g. keeping vowel quality fixed.

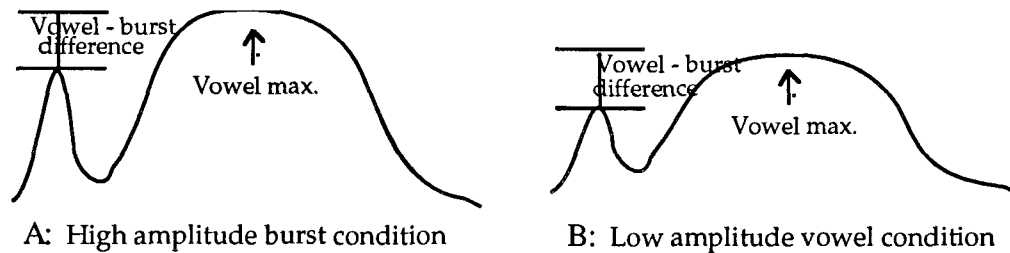


Figure 18. Two scenarios yielding a small difference in “vowel-burst” amplitudes.

As in the duration portion of the study, statistical analyses for each of the effects being tested below will reflect the two factors (independent variables) stop category and speaker identity, unless otherwise specified. In all cases, a highly significant main effect for speaker identity (at the $p < .0001$ level, usually) was found, unless otherwise reported. Speaker identity is probably a more important effect here than it was for duration, because of the less than optimal signal-to-noise ratio for these recordings. Because recordings were made on three separate occasions and in two different locations the factor “speaker identity” for this data comprises not only a difference in speaker, but the particular noise conditions that obtained when that speaker was recorded. Different recording conditions potentially contribute not only to both speaker identity as a significant category but also to significant interactions with stop category. (A high noise level could mask differences and yield apparent groupings across categories for a given speaker.) Thus, while Speaker D showed the greatest range of relative amplitude values, probably because a good signal-to-noise ratio allowed for small burst measurements, Speaker B showed the smallest range of values, consistent with the poorest signal-to-noise ratio.

3.2. Results

3.2.1. Relative amplitudes of word-initial vs intervocalic stops

Because significant durational differences were found for word-initial vs intervocalic stops (suggesting, following Butcher, that initial apicals may differ in their articulations from medial, contrastive apicals) the amplitude data was also tested along this dimension. Again, post-alveolar stops were necessarily excluded from the test because they do not occur initially. No significant difference was found between initials and intervocalics for vowel-burst differences, $F(1,114)=1.086$, $p=.2995$. Initial stops are not significantly higher or lower in amplitude than intervocalic stops. This result is plotted in Figure 19.

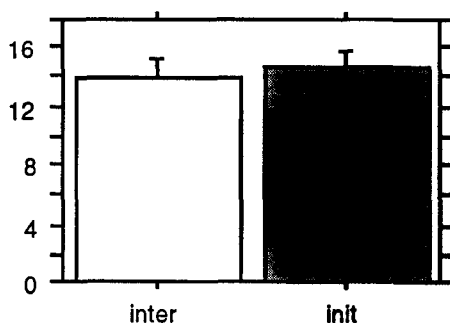


Figure 19. Mean vowel-burst amplitude differences for intervocalic vs initial tokens.

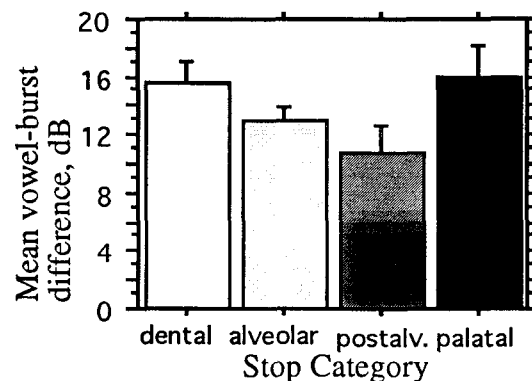


Figure 20. Vowel-burst differences in amplitude for Tiwi stop categories.

4.2.2. *Relative amplitudes of burst categories*

A two-factor ANOVA over all the data showed that vowel-burst differences distinguished all pairs of stop categories except dentals and palatals, which act as a group here. Postalveolars had the smallest vowel-burst differences, palatals and dentals the largest differences, and differences for alveolars fell in between, as can be seen in Figure 20. The main effect of stop category on vowel-burst amplitude was highly significant, $F(3,127)=12.096$, $p<.0001$. In paired post-hoc comparisons of means, over all vowel and word-position environments, each of the four categories was distinguishable from each of the others at the 95% significance level, with the exception of the palatal and dental categories.

For this test there was also a significant interaction effect between speaker and place ($F[12,127]=2.904$, $p=.0014$), taken to be an artifact of recording environment, as explained above. Despite the significant interaction term, the post-alveolar consistently showed small normalized differences across speakers; i.e. potentially the largest burst amplitudes. Palatals and dentals showed the largest differences across speakers (smaller potential burst amplitudes). The alveolar was variable across speakers.

Intervocalic environment has been shown not to be conducive to louder bursts (section 4.2.1.) Thus, the low vowel-burst difference for post-alveolars is not attributable to its restriction to medial environments. In order to determine with certainty which of the two scenarios in Figure 18 accounted for the small vowel-burst differences for post-alveolars, two additional tests were performed. These are described below.

The intervocalic alveolar, dental and palatal stops in this data subset appear in the word-final syllable. However, the post-alveolars are in antepenultimate position in 9 of 27 tokens (33%). (These are the post-alveolars in the word /kitaʔawíni/). A 3-factor ANOVA including speaker, stop category and position in the word as factors showed that statistically important differences do exist among amplitude maxima for vowels occupying different word positions; word-final syllable nuclei are lower in amplitude than antepenultimate nuclei. Thus, to verify that post-alveolars showed small vowel-burst differences by virtue of high-amplitude bursts rather than low-amplitude vowels, a second analysis was performed restricted just to word-final syllables. The effect remained statistically robust for the post-alveolars.

Effects of intrinsic vowel amplitudes were considered (/i/ is expected to be lower in energy than /a/, other factors being equal). Narrowing the data set even further, to control for vowel environment, the intervocalic environments **aTi** and **aTa** were separately examined. Results for **aTi** environments are shown in Figure 21 (recall that this environment excludes dentals). A two-factor ANOVA showed that each speaker had the smallest relative differences for the post-alveolar category, while speaker variability in the behavior of the alveolar and palatal categories made it impossible to conclude anything further. Two speakers showed greater differences for alveolars than palatals, two showed greater differences for palatals than alveolars, and one showed roughly equal mean differences, as shown in Figure 22 below.

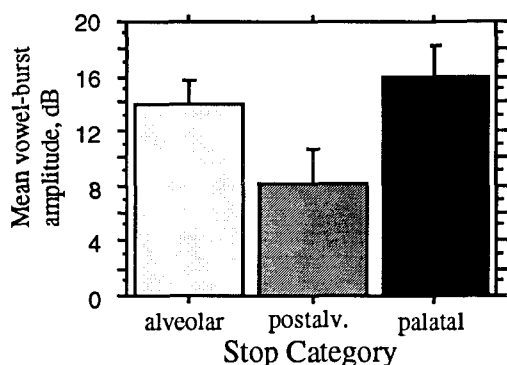


Figure 21. Mean vowel-burst amplitude differences for stop categories in **aTi** environments.

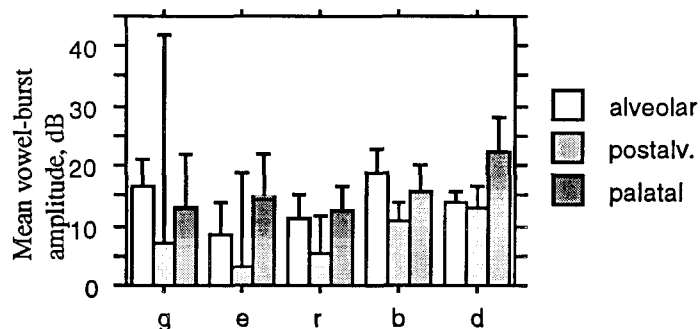


Figure 22. Mean vowel-burst amplitude differences for stop categories in **aTi** environments, by speaker.

For the comparison of relative amplitudes in **aTa** environments, a two-factor ANOVA showed that dentals have significantly higher vowel-burst amplitude differences than either alveolars or post-alveolars. Alveolars and post-alveolars did not differ significantly in this environment. As Figure 24 shows, four of the five speakers showed this trend of low amplitude dentals, while for Speaker B (for whom the poorest recording conditions obtained) the mean vowel-burst difference for post-alveolars just exceeded that for dental, and showed a large standard deviation.

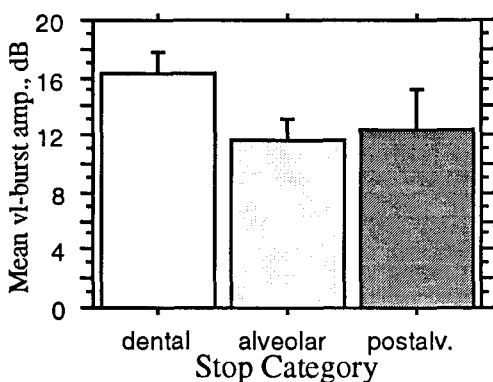


Figure 23. Mean vowel-burst amplitude differences for stop categories in **aTa** environments.

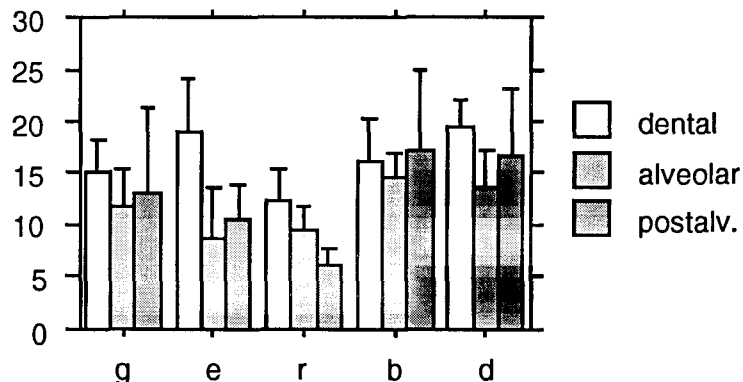


Figure 24. Mean vowel-burst amplitude differences for stop categories in **aTa** environments, by speaker.

Since vowel environment is controlled for in the latter two tests, it is safe to assume that significant differences arise from amplitude differences of bursts, rather than difference in vowel amplitudes. Thus, from Figure 21 we conclude that post-alveolars have the highest amplitude bursts among the stops, in /i/ environments. From Figure 23 we conclude that dentals have the lowest amplitude bursts, in /a/ environments. What is surprising is that alveolars are as quiet in amplitude as palatals in /i/ environments (Figure 21), but are up in the range of post-alveolars, in /a/ environments (Figure 23); that is, they maintain a constant relative amplitude (-12 dB) with respect to the following vowel. Compare the case for the post-alveolar, which shows a smaller difference (-8 dB) in the quieter /i/ environment, and a larger difference (-12 dB) in the environment of the higher amplitude vowel.

In sum, relative amplitude strongly distinguishes post-alveolar bursts as the loudest in /i/ environments. In /a/ environments, dental bursts are the lowest in amplitude. However, the variable behavior of alveolar bursts in the two environments means that they group with the quieter palatals on one hand (before /i/) and the louder post-alveolars on the other (before /a/). As in the case of duration, post-alveolars differentiate themselves far more clearly from the laminals than do the alveolars.

4.3. *Discussion of amplitude results*

Hypothesis 4 suggested that laminals would be lower in amplitude than apicals at the moment of the burst, because of the comparatively gradual release of the articulator. When looked at overall, this appeared to be the case. Figure 19 shows laminals grouping together, and while apicals are statistically significantly different from each other, they are both lower in vowel-burst differences than the laminal group. However, this result is misleading. When we look at vowel environments separately (Figures 21, 23) post-alveolars do stand out as loudest, and dentals as quietest, but alveolars covary with the amplitude of the following vowel. In /i/ environments they are indistinguishable from palatals; in /a/ environments they are indistinguishable from post-alveolars. These results seem to indicate that the post-alveolar is more resistant to coarticulation with the following vowel than is the alveolar. This is surprising, in light of Butcher's finding that among the four stops it is the apical alveolars that show the greatest stability in their articulations. It may be that for the alveolar in /i/ environments, the tongue blade and body behind the occlusion, while not making tectal contact, are nevertheless raised, making the general oral tract configuration more similar to that of palatals. But the post-alveolar, characterized by a highly specified articulatory program involving forward movement, may permit less coarticulation of the tongue blade and body with /i/. Here again, classificatory features seem to have less to predict about actual acoustics than tongue shape in general.

Our results show partial agreement with those of Shalev et al. (1993) for Toda, and Jongman et al. (1985) for Malayalam; dental bursts are quieter than alveolars. This at least suggests that the articulations in Tiwi are apical alveolar and laminal dental, similar to the Toda and Malayalam articulations.

5. SPECTRAL SHAPES

5.1. Procedure

5.1.1. *Data*

The subset of data used to examine burst spectra, shown in Table 7, consisted of coronals preceding the vowels /a/ and /i/ in either initial or intervocalic position. Spectra for the three male speakers were examined since there are more males in the set than females and the recordings for the male speakers had, in general, better signal-to-noise ratios than those for the female speakers. By examining data from only one sex, the problem of making comparisons across speaker-dependent frequency range differences was reduced.

Although the vowel environment Ta was chosen for the examination of dentals, alveolars and post-alveolars, as the most neutral of the available possibilities, the environment Ti was by necessity also used, in order to include a comparison of the palatal with alveolars and post-alveolars. Spectral information for bursts was obtained from CSL by centering a 12.8 ms Hamming window around the burst transient, (yielding a 78 Hz frequency resolution) and displaying a Fast Fourier Transform (FFT) spectrum of the frequency range 0-8000 Hz. Pre-emphasis (.90) was used to boost high frequencies. The procedure is illustrated in Figure 25. As in Dart (1991), a very brief time window was used in order to facilitate capture of just the burst transient itself, rather than a significant portion of frication. It was considered that spectral shape

at the moment of the burst would yield a more accurate representation of front cavity shape at the moment of release than would a spectrum including frication (in which the cavity shape is changing.) Spectra were output as data files, each consisting of the amplitudes of 100 frequency values at 80 Hz intervals, which allowed the spectra to be superimposed and averaged.

Table 7: Data subset used for spectral shape of bursts

	Vowel Environment	alveolar	post-alveolar	dental	palatal
Initial stops	#_a	tarina taɲini	--	tampinaɲa	
	#_i	tiɲata tinimuli	--		tiɲaka tiɲaka
Intervocalic stops	a_i	yati	pulaɲi		pikaɲi paɲipaɲuwu
	a_a	tiɲata	kiɲatawini	piɲata	
	u_a	kurumuta			
	o_a		woɲa	poɲa	

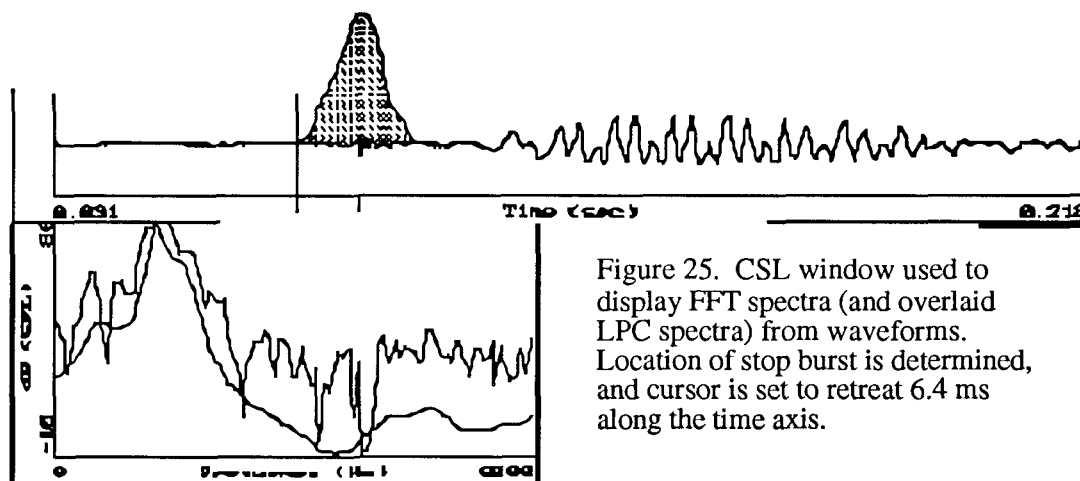


Figure 25. CSL window used to display FFT spectra (and overlaid LPC spectra) from waveforms. Location of stop burst is determined, and cursor is set to retreat 6.4 ms along the time axis.

5.1.2. Analysis

While spectral information was not subjected to statistical analysis in this study, individual tokens for a given category of burst and speaker were overlaid and examined together so as to assure that the spectra shown in the resulting composite averages accurately represented the general shape of spectra for each stop category for each speaker.

Initially it was assumed that preceding vowel environments would not affect burst spectra, because most stops involved a period of silent closure before the burst. However, a first examination of the data showed that a preceding rounded environment can indeed affect the burst spectrum, by lowering amplitudes, especially of frequencies under 1200 Hz as compared with their unrounded counterparts. Presumably there is perseveration of rounding from the preceding vowel through the consonant burst. Figures 26a and 26b show cases of this effect. In each of the graphs below, abscissas are shown on a logarithmic scale to better approximate the perceptual weighting of these frequencies. Graphs were smoothed using a five-point moving average of values, for the hundred increments between 0 and 8000, which is why frequency values do not extend below 200 Hz. Ordinates show amplitudes of each averaged point in dB.

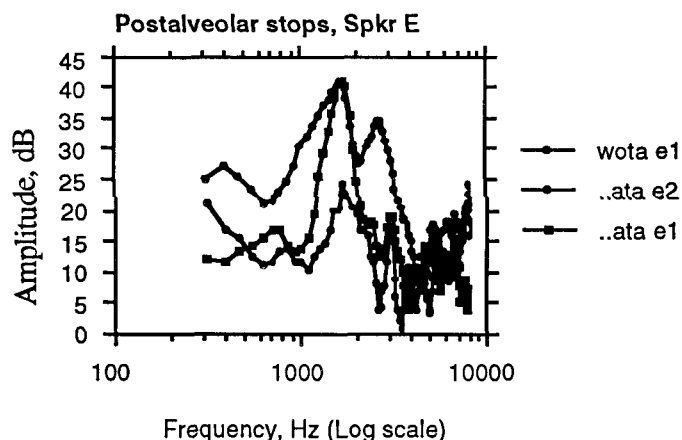


Figure 26a. Postalveolar stop spectra, Speaker E, rounded and unrounded vowel environments. Note low peak at 1200 Hz for stop burst in /woʔa/.

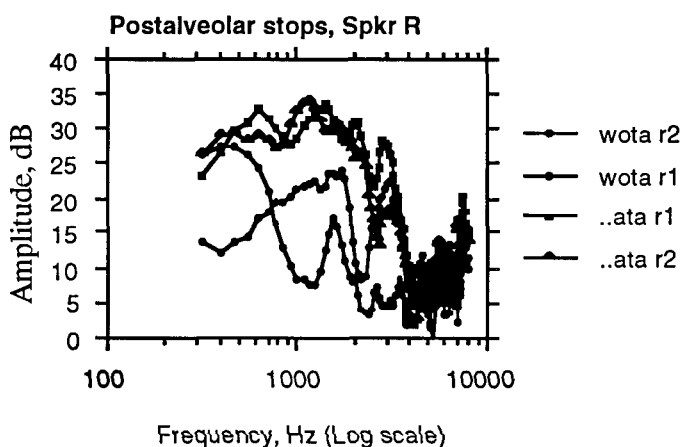


Figure 26b. Postalveolar stop spectra, Speaker R, rounded and unrounded vowel environments. The two lower curves are for the stop burst in /woʔa/.

Cases which departed from the norm in amplitude but retained the general shape of other exemplars, (as in the lowest amplitude curve in Figure 26a) were retained, but cases which clearly departed in both amplitude and general shape (as in the two low amplitude curves in Figure 26b) were excluded from averaged data.

A second strong effect of vowel environment was found for each of the stop categories. Spectra for bursts followed by /i/ were very characteristic of the spectrum for /i/ itself. Hence, it was not possible to characterize palatal spectra separate from other stops.

5.2. Results

Spectral averages for the Ta environment are shown in Figure 27 for the three male speakers. Many of the spectra in Figure 27 show a low frequency peak of high energy below 1 kHz. While this is not broad-band noise, this peak did appear to represent either an external noise source, or an extra resonance unrelated to the coronal articulations, characteristic to different extents of different speakers. Note that it is most characteristic of Speaker D, to a lesser extent of Speaker R, and least characteristic of Speaker E. (Initially, a plausible alternative appeared to be that this low frequency energy peak represented F1 of the following /a/, but it also

occurs in the spectra of Speaker D for Ti environments, where there is also a clear F1 peak at about 300 Hz.) Since it appears to be related to characteristics of the speaker or the recording environment, this peak was disregarded as a potential differentiating characteristic between coronals. Moreover, above about 7 kHz all of the spectra behave similarly, rising in response to the band of external noise between 8 and 11 kHz mentioned earlier. Thus, usable differentiating information was located between 1 and 7 kHz. This range is, however, the region to which the human auditory system is most attuned.

Each of the spectral averages has its major zero (low amplitude area) between 3 and 4 kHz. This seems to be a consistent factor which identifies the group “coronal” as a whole in Tiwi. The consistency of this result is surprising, considering that Dart (1991) found zeroes ranging from 4 to 7 kHz for Malayalam coronals. Although the spectra have yet to be compared with non-coronals, this zero seems to be a robust contender for a characteristic of Tiwi coronals in general.

These composite spectra, with their midfrequency zero and few peaks, are not easily classified as either “diffuse” or “rising” in Jakobson, Fant and Halle’s terms. A more useful measure in differentiating among dental, alveolar and post-alveolar categories seems to be the bandwidth of the first major peak above 1 kHz (centered in each case approximately between 1.7 and 2 kHz, which we take to be the approximate F2 locus). To obtain comparable measures of bandwidth for each category of stop, the frequency bandwidth (measured by hand from composite spectra) is shown at 6 dB down from the maximum amplitude of the peak, as a horizontal line in each of the panels in Figure 27.

For Speakers D and E in the top two rows, the alveolar has a broader first peak bandwidth than the post-alveolar (approximately 700 Hz as opposed to 600 Hz for D and 1900 vs 1800 Hz for E), and a second high amplitude excursion immediately following the first. For these speakers, the post-alveolar has an isolated, narrow-bandwidth major peak, without a second high-amplitude peak. This may indicate that F2 and F3 are joined in the post-alveolar spectrum, forming a single peak. The contrast between Speaker R’s alveolars and post-alveolars in the bottom row does not pattern with the two other speakers’ as there is no narrow-bandwidth peak in the post-alveolar. This may be because there is masking noise from other sources.

Dental bursts for each speaker are marked by the smaller prominence of any peak; i.e. amplitude excursions are not so extreme. The first peak, as well as the second “hitch” or plateau following it are broader in bandwidth than either of the apicals (2000 and 1800 Hz respectively for D and E), implying a greater diffusion of energy.

Dental

Alveolar

Post-alveolar

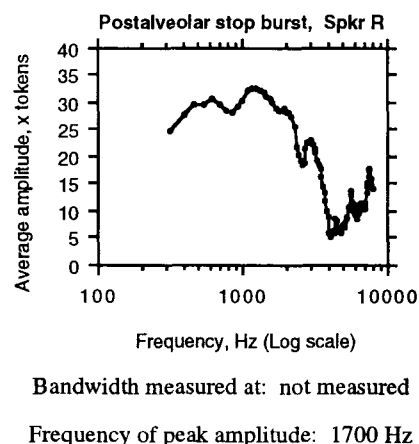
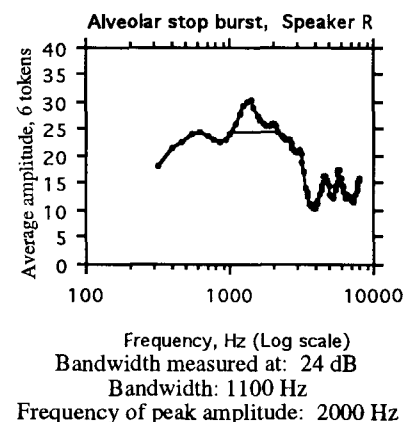
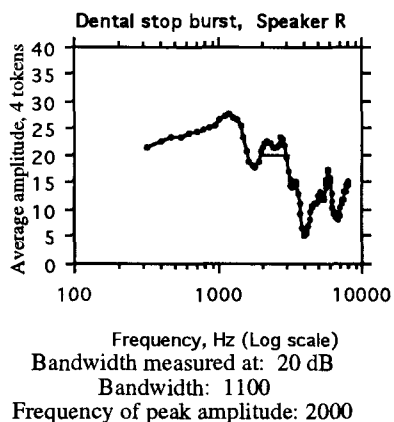
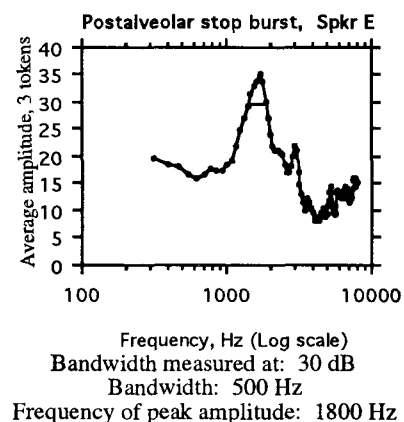
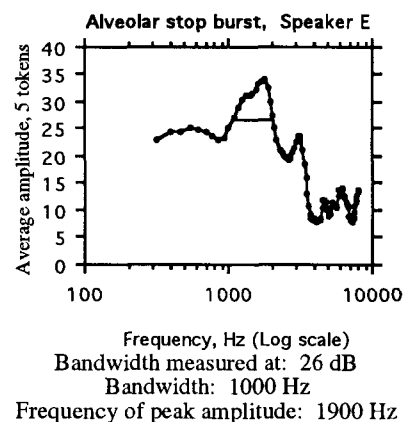
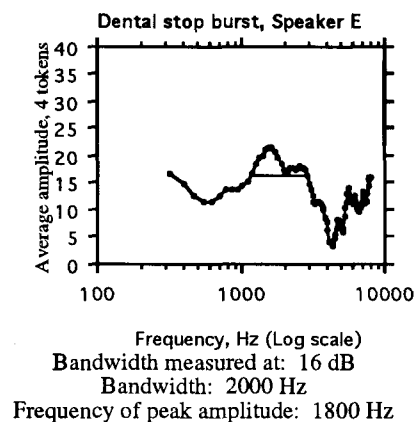
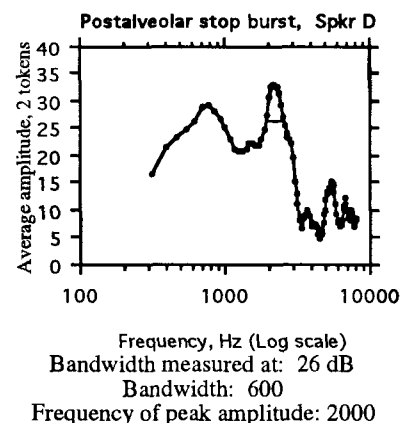
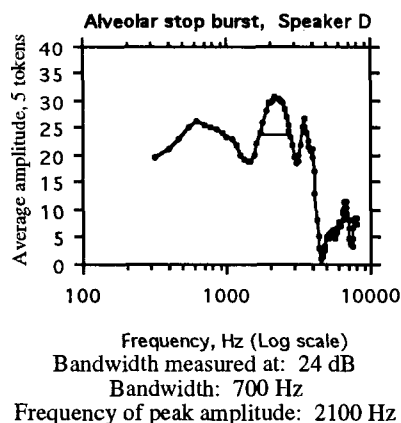
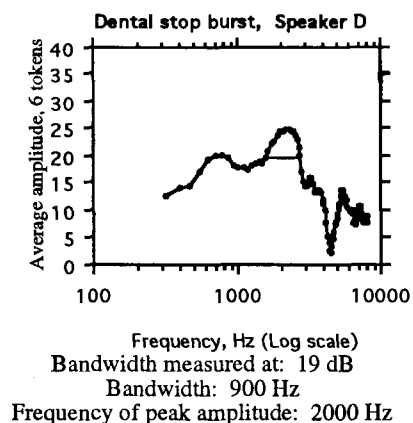


Figure 27. Mean spectra of coronal stop bursts before /a/ for three male speakers.

5.3. Discussion of spectral measurements

Hypothesis 5 suggested that [-anterior] stops would show a narrower concentration of energy than [+anterior] stops. As it happens this data did not allow us to characterize palatals apart from the vowel /i/. The energy for the ([-anterior]) post-alveolars is indeed less distributed than in either of the [+anterior] segments. However, there seems to be less a discrete split between [-anterior] and [+anterior] than a continuum from dental to post-alveolar. There is a range of differences in energy concentration from dentals (least concentrated) to post-alveolars (most concentrated.) Again, this seems less related to the classificatory feature [anterior] than it does to a more scalar measurement of anteriority which reflects the size of the cavity in front of the constriction.

Recall that Stevens and Keyser (1989) suggest that [-anterior] can only be strongly salient in [-coronal] segments. However, Lahiri et al. (1984) found that coronal spectra can be diffuse-flat. As such, a high amplitude mid-frequency peak can, and does, seem to characterize the Tiwi alveolars and post-alveolars. Dart (1991) found relatively less peaked spectra for apicolaminal dentalveolars, increasingly peaked spectra for apical alveolars and a lower frequency peak for (apical or sublaminal) post-alveolars, in both Malayalam and 'O'odham. These results are broadly consistent with the Tiwi data.

Perkell, Boyce and Stevens (1979) observe that a sublaminal cavity lowers acoustic resonances. For the Tiwi post-alveolars, we surmise that the resonance most affected is F3; spectrograms show clear evidence of a common locus for F2 and F3 (these formant transitions look very much like velars.) Halle and Stevens (1989) in examining Polish fricatives, show an amplitude zero at 4 kHz for retroflex /ʂ/, but they attribute the peak to a merging of F3 and F4. For Tiwi post-alveolars the meeting point seems to be uncontroversially F2 and F3. It is this common locus which creates the isolated, dominant peak we observe in post-alveolar spectra.

6. CONCLUSION

The contrast between coronal stops of different categories, as in Tiwi, is relatively unusual among the world's languages. Languages with such features allow an opportunity to examine acoustic concomitants of regular but subtle differences in place of articulation, shape of the active articulator, and configuration of the vocal tract as a whole.

Let us summarize the acoustic characteristics of the Tiwi coronals and relate them to probable articulations. The dental allophone of the laminal phoneme ([-apical] [+anterior]) has intermediate duration, a low burst amplitude and a relatively diffuse-energy spectrum. This is expected for an articulation with a wide constriction in the front of the mouth. The post-alveolar phoneme ([+apical] [-anterior]) is well differentiated in nearly every domain; it is short in duration, high in burst amplitude, and has a narrow distribution of spectral energy. This is consistent with employment of a small, forward-moving articulator without narrowing of the oral tract behind it. Given the lowering of F3, there is probably a significantly large front cavity involved, suggesting that the articulation in Tiwi is probably sublaminal. The palatal allophone of the laminal phoneme ([-apical] [-anterior]) is differentiated by long VOT and associated frication, showing evidence of a long constriction. The alveolar phoneme ([+apical] [+anterior]) appears as the least distinctive, as it is often grouped with one or more of the other categories. However, it differs from the post-alveolar in voiceless closure duration, VOT, burst amplitude and bandwidth of its major spectral peak. These differences are consistent with it being a more forward articulation than the post-alveolar, probably not involving movement during closure. It differs from the palatal in VOT, suggesting a lighter articulator than the palatal. Its greater relative amplitude than the dental points to a difference in constriction size between them.

What do Tiwi speakers use to hear differences between these relatively rare oppositions? Three of these stops contrast phonologically. Let us consider each contrast in turn. In vowel environments other than /i/, post-alveolar /t̪/ is distinguished from both dental /t̪/ and alveolar /t/ in having a higher burst amplitude, being shorter in voiceless closure and VOT, and having an isolated narrow-bandwidth spectral peak. Dental /t̪/ is distinguished from alveolar /t/ by a lower amplitude burst and more distributed spectrum. When the vowel /i/ follows, dental /t̪/ is realized as palatal [t̪]. Postalveolar /t̪/ is shorter in voiceless closure and VOT and higher in burst amplitude than both alveolar /t/ and palatal [t̪]. It has a narrower spectral energy distribution than alveolar /t/. The alveolar and palatal are distinguished by VOT. Thus, Hypothesis 1 is validated: although the durations, relative amplitudes and spectral shapes of bursts cannot by themselves differentiate all the stop categories, taken together they do make the required distinctions.

Earlier, Dart (1991) looked for, but did not find any “one property (that) consistently differentiates the apicals from the laminals.” Despite increased focus on components of duration and average spectra, as well as the inclusion of a study of relative amplitudes, the result is the same in this study. Similarly, the present study does not find any one property that separates anterior from non-anterior coronals.

Thus, the more specific Hypotheses 2 through 5 failed in their predictions. There was no straightforward mapping between the features [apical] and [anterior] and acoustic correlates in any of the tests presented above. Instead, these classificatory phonological features seem to be mediated by a phonetic implementation layer which arises (partly) from feature specifications. The phonetic parameters, or determinants, in this layer include oral tract configuration, articulator mass and movement during closure location. It is this intermediate layer which relates in a direct way to acoustics.

In the larger picture, these results indicate support for a theory in which classificatory features relate directly to production, but not to perception; there could be no “feature detectors” which decode simple or invariant relationships between features and acoustics, because, in this case, no such relationships exist. The perceptual apparatus is likely to be significantly more sophisticated, retrieving classificatory feature values from a relatively opaque signal.

For stops, duration information contributes to an acoustic “picture” of the cavity behind the constriction. Spectral information yields a picture of the cavity in front of the constriction. Burst amplitude and VOT give a picture of the active articulator. Formant transitions, not studied here, would further distinguish the stops.

The absence of simple correlations between features and acoustic properties is likely to be highlighted by extending the present study to nasals, which have the same articulatory contrasts as the stops in Tiwi. Nasals, however, do not have VOTs, nor burst spectra, nor burst amplitudes comparable to stops. Therefore, these properties cannot relate to the articulatory features of nasals. Instead, different properties, such as nasal formants and zeroes, must be examined.

We have assumed that [apical] and [anterior] are indeed phonologically relevant in Tiwi, as determined by rule governed behavior, particularly distributional patterns. Unless this assumption is wrong, the results found here lend weight to the idea of the primary importance of articulation rather than acoustics in defining distinctive features.

Acknowledgments

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Appendix: List of words used in duration study

Tiwi word	English Gloss
alitiwíyi	<i>female kangaroo</i>
erepuṭara	<i>lip</i>
kitatawíni	<i>bread</i>
kumúti	<i>beard</i>
kurumúta	<i>upper arm</i>
milikúti	<i>big toe</i>
minapúti	<i>cold (A)</i>
muritiwa	<i>neck</i>
ṇawatiwi	<i>people (pl., excl.)</i>
patipaṭúwu	<i>turtle egg</i>
paṭiwáni	<i>dead</i>
pikáti	<i>swordfish</i>
piráṭa	<i>rice</i>
pitára	<i>eyes</i>
poaliti	<i>beard</i>
póṭa	<i>bone</i>
puláti	<i>milk</i>
taṇaríma	<i>camp</i>
taṇíni	<i>stick</i>
taríṇa	<i>back of head</i>
tinimúli	<i>eyebrow</i>
tiṇáta	<i>beach</i>
tíwi	<i>people</i>
tokampíni	<i>bird (m)</i>
tokampúṇa	<i>bird (f)</i>
toṇuláka	<i>canoe</i>
tuṭutuṭi	<i>move around</i>
tuulúa	<i>head</i>
ṭampináḷa	<i>cliff</i>
ṭapára	<i>moon</i>
ṭapinári	<i>morning</i>

ṭukwantáṇa	<i>back</i>
ṭikapúti	<i>cold (N)</i>
ṭiráka	<i>wallaby</i>
ṭitáka	<i>swordfish</i>
ṭiti	<i>bad, ugly</i>
wóṭa	<i>bush</i>
wuratiṇa	<i>forehead</i>
yáti	<i>one</i>