Tongue body and tongue root shape differences in N|uu clicks correlate with phonotactic patterns

Amanda L. Miller

1. Introduction

There is a phonological constraint, known as the Back Vowel Constraint (BVC), found in most Khoesan languages, which provides information as to the phonological patterning of clicks. BVC patterns found in N|uu, the last remaining member of the !Ui branch of the Tuu family spoken in South Africa, have never been described, as the language only had very preliminary documentation undertaken by Doke (1936) and Westphal (1953–1957). In this paper, I provide a description of the BVC in N|uu, based on lexico-statistical patterns found in a database that I developed. I also provide results of an ultrasound study designed to investigate posterior place of articulation differences among clicks.

Click consonants have two constrictions, one anterior, and one posterior. Thus, they have two places of articulation. Phoneticians since Doke (1923) and Beach (1938) have described the posterior place of articulation of plain clicks as velar, and the airstream involved in their production as velaric. Thus, the anterior place of articulation was thought to be the only phonetic property that differed among the various clicks. The ultrasound results reported here and in Miller, Brugman et al. (2009) show that there are differences in the posterior constrictions as well. Namely, tongue body and tongue root shape differences are found among clicks. I propose that differences in tongue body and tongue root shape may be the phonetic bases of the BVC.

The airstream involved in click production is described as *velaric airstream* by earlier researchers. The term *velaric airstream* is replaced by *lingual airstream* by Miller, Namaseb and Iskarous (2007) and Miller Brugman et al. (2009). The majority of consonants found in the world’s languages are produced using a *pulmonic egressive airstream*, meaning that sound is produced on the air pushed out of the lungs under the control of the respiratory muscles. Click sounds, on the other hand, are produced when air is rarefied between the two constrictions as the tongue dorsum moves backward and downward. The click burst occurs when the anterior constriction is released, allowing air to rush into the vacuum made by the
tongue. The release of the posterior constriction is pulmonic egressive, because air is being pushed outward by the lungs. Due to the proximity of the releases of the anterior and posterior constrictions, the posterior release is inaudible in plain clicks, and there is often no visible pulmonic burst. However, I will provide data in this paper on the patterning of a class of clicks that have an audible pulmonic burst, which I refer to as linguo-pulmonic contour segments. The terms complex segments and contour segments refer to the distinction made by Sagey (1990). Complex segments are sounds that have two constrictions that are nearly simultaneous; and contour segments are single sounds that are sequences of articulations (Sagey 1990). In this paper, all clicks are referred to as complex following Sagey (1990) and Miller, Brugman et al. (2009), while affricates and linguo-pulmonic contour segments are referred to as contour segments.

I provide a model for click consonants that follows Zsiga (1997) and Fujimura (2000) in having both phonetic and phonological components. The phonetic component is based in Articulatory Phonology (Browman and Goldstein 1989). The mapping between the two components of the grammar may be viewed as an implementation of what Fowler (1980) refers to as coordinative structures.

1.1. The Back Vowel Constraint

Traill (1985) proposed a constraint that rules out the co-occurrence of plain clicks with front vowels to account for the lexical gap of words containing clicks and front vowels in ǃXóõ, and stated it in terms of the feature [back]. Since plain clicks were assumed to all have velar posterior constrictions, they were all assumed to be marked for the feature [+ back]. He called the constraint that rules out the co-occurrence of certain consonants with front vowels – the Back Vowel Constraint (BVC), and stated it in the form of the implication provided in (1):

\[
\text{(1) The Back Vowel Constraint} \\
\text{If } C_1 V_1 <+\text{back} \text{ then } C_1 V_1 <+\text{back} <+\text{back} 
\]
The existence of front vowels following dental and palatal clicks is captured by a rule, which Traill (1985) calls Dental Assimilation (DA). Sagey (1990) and Clements and Hume (1995) use the feature [+anterior] to classify the dental [ǀ] and palatal [ǂ] clicks separately from the central alveolar [ǃ] and lateral alveolar [ǁ] clicks. The Dental Assimilation rule in (2), adopted from Sagey (1990), crucially requires both dental and palatal clicks to be [+anterior]. This is justified by the fact that palatal clicks have a long constriction, which covers a large area from the dental to the palatal region.

(2) Dental Assimilation (DA)
\[ a \rightarrow \mathring{a}, i / [+\text{ant}] \_ _ i, n \]

Miller-Ockhuizen (2000) showed that this so-called Dental Assimilation in Ju’hoansi is not an assimilatory process, but rather a phonetic process of co-articulation, by showing that it does not change a back vowel to a front vowel categorically. Rather, co-articulation fronts a back vowel slightly following dental and palatal clicks, but this is largely inaudible. A separate process of height harmony raises the low vowel /a/ before the high vowels [i] and [u], which yields [ơ], irrespective of the preceding consonant. Thus, DA cannot account for the presence of [i] following dental and palatal clicks in that language, as the co-articulatory process is not strong enough to change [ơ] to [i] even between a dental click and a front vowel. Miller-Ockhuizen (2000, 2003) claims that there must be a phonological difference in the clicks themselves following Sands (1991) and Johnson (1993), and that the BVC must refer to that difference, targeting only central alveolar [ǃ] and lateral alveolar [ǁ] clicks, along with pulmonic uvular consonants. Miller-Ockhuizen (2003) analyses the central alveolar [ǃ] and lateral alveolar [ǁ] clicks as having a [pharyngeal] feature specified on the posterior constrictions as in (3), and captures the BVC as a co-occurrence constraint against pharyngeal consonants and front vowels as in (4).

(3) Specification of posterior constrictions in Ju’hoansi clicks
(Miller-Ockhuizen 2003)

<table>
<thead>
<tr>
<th>Type</th>
<th>Constriction</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dental Click</td>
<td>[ǀ]</td>
<td>unmarked for pharyngeal</td>
</tr>
<tr>
<td>Central Alveolar</td>
<td>[ǃ]</td>
<td>[pharyngeal]</td>
</tr>
<tr>
<td>Lateral Alveolar</td>
<td>[ǁ]</td>
<td>[pharyngeal]</td>
</tr>
<tr>
<td>Palatal click</td>
<td>[ǁ]</td>
<td>unmarked for pharyngeal</td>
</tr>
</tbody>
</table>
Classification of dental and palatal clicks together, opposite the central and lateral alveolar clicks, in terms of the place of articulation of the anterior constriction is problematic, since alveolar clicks have an anterior constriction location in between the anterior dentals and further back palatals.

The unexplained patterning of clicks in terms of anterior place features caused Sands (1991) and Traill (1997) to classify clicks in terms of the acoustic feature [acute] vs. [grave] proposed by Jakobson, Fant and Halle (1952), which classifies sounds based on their spectral frequencies (for clicks and pulmonic stops, it is the frequencies of their bursts). [Acute] sounds are higher frequency than [grave] sounds. However, Miller-Ockhuizen (2000) showed that labial clicks and labial pulmonic consonants do not pattern together in !Xôô, and thus [acute] vs. [grave] could not correctly classify clicks and pulmonic stops targeted by the BVC.

1.2. Phonetic differences among clicks

Miller, Namaseb and Iskarous (2007) and Miller, Brugman et al. (2009) have, by means of ultrasound, found that the palatal click [ǂ] involves tongue root raising, while the alveolar click [ǃ] involves tongue root retraction, in Khoekhoe and Ngwuu respectively. Miller, Scott, et al. (2009) have shown, using high frame rate ultrasound data, that posterior place of articulation differs among the four click types in Mangetti Dune !Xung. The palatal click displays the farthest back posterior constriction. The lateral and dental clicks display slightly more forward constrictions, and the posterior constriction of the alveolar click is the farthest forward. Contrary to traditional descriptions, none of the observed clicks has a velar posterior constriction location. Rather, the posterior constriction locations are all uvular. Thus, classification of clicks in terms of their BVC patterns does not match up with differences in place of articulation of the posterior constrictions.

Thomas-Vilakati (2009) shows using electropalatography and airflow data that IsiZulu clicks differ in terms of their rarefaction gestures. Some
use tongue centre lowering and some tongue dorsum retraction. She suggests, based on indirect airflow measurements, that the palato-alveolar click [ǃ] in IsiZulu must use mainly tongue centre lowering. Miller, Scott et al. (2009), use high frame rate ultrasound data to show that the dental and palatal clicks in Mangetti Dune !Xung display tongue centre lowering, while the central alveolar click displays tongue centre lowering, tongue tip retraction and tongue root retraction. The lateral alveolar click displays the widest region of tongue centre lowering, and involves formation of a low tongue centre plateau (as opposed to the narrow tongue well seen with the other clicks). Thus, the alveolar click, [ǃ], which is subject to the BVC, involves tongue root retraction. Further investigation is needed to fully understand the dynamics of the lateral click, since only sagittal data have been analysed up to this point. These recent findings then suggest that the differences in the articulation of the posterior constrictions among clicks may help elucidate the phonetic bases of BVC patterns.

1.3. Clicks with airstream contours

I now turn to another class of clicks found in Khoesan languages, which Traill (1985, 1997), Bell and Collins (2001) and Nakagawa (2006) refer to as ‘uvular’ clicks, but Miller, Brugman et al. (2009) refer to as linguo-pulmonic stops, that is, clicks that have a contour in airstream. In this paper, I shall refer to these sounds as clicks with airstream contours. Traill (1985), Ladefoged and Traill (1994) and Ladefoged and Maddieson (1996) claim that these ‘uvular’ clicks differ from ‘velar’ clicks (plain clicks) mainly in their posterior places of articulation, as seen in Table 1. Bell and Collins (2001) and Nakagawa (2006) have used the same symbols for ŽHoan and G|ui respectively. No phonological account of the claimed posterior place contrasts in Table 1 has been offered, and their co-occurrence patterns with front vowels, e.g. their BVC patterns, are unknown.

Miller, Brugman et al. (2009) have shown that clicks in N|uu that are phonetically similar to clicks transcribed with contrastive ‘uvular’ posterior place of articulation in !Xóõ, ŽHoan and G|ui, do not differ in terms of their posterior constriction locations from those termed ‘velar’ clicks.
Table 1. Claimed contrasts in posterior place of articulation (L&T refers to Ladefoged and Traill 1994; L&M refers to Ladefoged and Maddieson 1996; Miller refers to Miller, Brugman et al. 2009).

<table>
<thead>
<tr>
<th></th>
<th>L&amp;T, L&amp;M</th>
<th>L&amp;T, L&amp;M</th>
<th>Miller</th>
<th>Miller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labial</td>
<td>[ʘk]</td>
<td>[ʘq]</td>
<td>[ʘ]</td>
<td>[ʘq]</td>
</tr>
<tr>
<td>Dental</td>
<td>[ǀk]</td>
<td>[ǀq]</td>
<td>[ǀ]</td>
<td>[ǀq]</td>
</tr>
<tr>
<td>(Central) Alveolar</td>
<td>[ǃk]</td>
<td>[ǃq]</td>
<td>[ǃ]</td>
<td>[ǃq]</td>
</tr>
<tr>
<td>Lateral Alveolar</td>
<td>[lk]</td>
<td>[lq]</td>
<td>[l]</td>
<td>[lq]</td>
</tr>
<tr>
<td>Palatal</td>
<td>[k]</td>
<td>[q]</td>
<td>[l]</td>
<td>[q]</td>
</tr>
</tbody>
</table>

Miller, Brugman et al. (2009) show that these clicks have an extended pulmonic airstream component involving audible posterior release bursts. Thus, they differ from so-called ‘velar’ clicks in terms of airstream, as they are single segments, which are produced with a loud lingual burst, followed by a second audible pulmonic burst that is the acoustic result of the posterior constrictive release.

Ladefoged and Maddieson (1996) note that the posterior release in the so-called ‘uvular’ clicks is pulmonic, but they state that all clicks have a pulmonic posterior release. Miller, Brugman et al. (2009) show that while there are no posterior bursts in the N|uu clicks which were claimed to have a ‘velar’ pulmonic release (see Table 1), there is a shift from lingual airstream to pulmonic airstream. So-called ‘velar’ and ‘uvular’ clicks differ in the duration of the tongue dorsum lag phase, the phase that Thomas-Vilakati (1999) describes as the time that the tongue dorsum constricts stays in place after the release of the anterior constrictor. In the so-called ‘velar’ clicks, the tongue dorsum and root are released nearly simultaneously with (in palatal clicks) or shortly after the release of the anterior constrictor (in alveolar clicks), while in the so-called ‘uvular’ clicks, the posterior constrictor involving the tongue dorsum and root is maintained for a long interval following the anterior release. Given the timing, Miller, Brugman et al. (2009) represent plain clicks as fully lingual complex stops, and so-called ‘uvular clicks’ are represented as contour segments that are complex stops in the closure phase, and pulmonic simple stops in the release phase. I continue to use the symbol [q] to mark the release for these clicks as a matter of convenience following Miller, Brugman et al. (2009), although the posterior release location appears to be front uvular for [ǃq], but back uvular for [i̯q], analogous to the posterior constrictor locations found for [ǃ] and [i].
Figure 1. Waveforms of the 5 N\textsubscript{uu} clicks and 5 linguo-pulmonic stops (clicks with airstream contours) in the words (a) [Ou\textsubscript{uu}] ‘son’; (b) [Qq'uiua] ‘sweat’; (c) [lu'uu] ‘boil’; (d) [luu] ‘tobacco’; (e) [luu] ‘acacia’; (f) [lqi] ‘ashes’; (g) [luu] ‘grasshopper’; (h) [luu] ‘urine’; (i) [luuke] ‘fly’; and (j) [luu] ‘neck’ (Speaker Katrina Esau).
Figure 1 provides waveforms showing the contrast between plain clicks, and clicks with airstream contours. As can be seen, the plain clicks have a single release burst formed by the release of the anterior constriction, and no acoustic signature of the posterior release. That is, the posterior release is inaudible. On the other hand, the clicks with airstream contours have both a clear click burst, which is the release burst of the anterior constriction that is made while the posterior constriction is held in place, and an audible second release burst resulting from the release of the posterior constriction. Since the anterior constriction has already released, this second burst is produced on a pulmonic airstream.

Miller, Brugman and Sands (2007) provide duration data for the four contrastive plain clicks, and the four clicks with airstream contours, in N|uu. The data show that the clicks with airstream contours have a second silent interval following the click burst with a mean of 40 ms, while there is no second silent interval in the plain clicks. Pulmonic bursts, which result from the release of the posterior constrictions in the clicks with airstream contours, are about 10 ms; while the plain clicks do not exhibit posterior bursts. The click bursts that result from the anterior releases range from 10-20 ms, and Voice Onset Time phases are about 20 ms. Each of these phases is similar in duration for the plain clicks and the clicks with airstream contours that have the same anterior places of articulation.

This study is similar in some aspects to Miller, Namaseb and Iskarous (2007) and Miller, Brugman et al. (2009). This paper differs from both of these earlier papers in that it provides a detailed lexical database study based on field recordings of the endangered Khoesan language N|uu recorded by the author and a team of linguists. Miller, Namaseb and Iskarous investigated Khoekhoe patterns. Miller, Brugman et al. (2009) focused on describing the inventory of N|uu clicks, and did not report on N|uu phonotactics. Though both report ultrasound data, this paper contains improved ultrasound traces that are plotted with the palate, and are discussed in more detail related to the phonotactic patterns. Miller (2010) provides an overview of known phonological patterns of clicks. The BVC patterns are only a small section of that paper. The linguistic analysis focuses on phonological features, rather than the phonetic model proposed here.

In this paper, I provide the results of two experiments. In section 2, I provide the N|uu consonant inventory. In section 3, I provide information about the methods, data collection and subjects used in this paper. In experiment 1, reported on in section 4, I provide lexico-statistical patterns
from a database study in N|uu showing that there are two classes of clicks with respect to their patterning in the Back Vowel Constraint. I show that clicks with airstream contours in N|uu pattern the same as plain clicks with respect to the BVC. In experiment 2, reported on in section 5, I provide ultrasound traces from a single speaker of N|uu, illustrating that it is tongue body and tongue root shape differences that are the phonetic bases of the lexical patterns shown in experiment 1. In section 6, I provide a model for click articulation in terms of Browman and Goldstein’s Articulatory Phonology, and in section 7, I conclude the paper.

2. N|uu consonant inventory

The N|uu consonant inventory described in Miller, Brugman et al. (2007, 2009), is provided in this section. Miller, Brugman et al. (2007, 2009) adopt a framework whereby airstream is used as a dimension to describe consonants, in addition to the standard place of articulation and manner of articulation dimensions. In the standard IPA consonant chart, consonants are separated into pulmonic and non-pulmonic consonants, and the full range of closure and release properties found on clicks are not included in the standard IPA consonant chart. This is much like aspiration, which is included as a diacritic in the standard IPA consonant chart (IPA 2006), but aspirated stops are included as a separate row in the consonant chart for Hindi where they serve as contrastive consonants (IPA 2006). In this paper, the N|uu stop inventory is presented in three tables based on the phonological categories of simple segments, complex segments and contour segments, with the complex vs. contour segment distinction used following Sagey (1990). Within each table, the rows represent manner of articulation, and the columns represent place of articulation as in the standard IPA chart. The airstream dimension is also used to group consonants within each table following Miller, Brugman et al. (2009). Glottalic airstream is the airstream used for ejectives. The full consonant inventory is provided in Miller, Brugman et al. (2009).

Table 2 provides the group of simple pulmonic stops. Table 3 provides the class of complex segments; that is clicks that are produced with two simultaneous constrictions, and a lingual airstream mechanism. These clicks are all those that are referred to earlier in this paper as plain clicks, and that were referred to in earlier descriptions as velar clicks. The term lingual airstream replaces velaric airstream mechanism, following Miller,
Namaseb and Iskarous (2007) and Miller, Brugman et al. (2009), because the posterior constriction in clicks is not velar.

Table 4 provides the class of N|uu contour segments, segments that are sequences of articulations: affricates, that are stops in the closure phase with fricated release phases, and linguo-pulmonic and linguo-glottalic segments that have contours in airstream (e.g. clicks with an extended posterior constriction). These are the stops that were previously termed *uvular* clicks by Ladefoged and Traill (1994) and Ladefoged and Maddieson (1996). With acoustic data, the only way to identify the airstream of a stop is by looking at the stop bursts. Waveforms of the stop bursts for plain clicks, and clicks with a pulmonic release are seen above in Figure 1. Recall that contour segments in airstream are visible as such based on the presence of a typically higher amplitude lingual burst at the release of the first stop interval, and a typically lower amplitude pulmonic stop burst, which occurs at the end of the second silent interval formed by the extended posterior constriction.

**Table 2.** N|uu simple stops

<table>
<thead>
<tr>
<th>Pulmonic</th>
<th>Central</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stop</strong></td>
<td><strong>p b</strong></td>
<td>(t) (d)</td>
</tr>
<tr>
<td></td>
<td>c cʰ j</td>
<td>cʰ j</td>
</tr>
<tr>
<td></td>
<td>k kʰ g</td>
<td>q</td>
</tr>
<tr>
<td></td>
<td>(? )</td>
<td></td>
</tr>
<tr>
<td><strong>Nasal</strong></td>
<td><strong>m n</strong></td>
<td><strong>p η</strong></td>
</tr>
</tbody>
</table>

**Table 3.** N|uu complex stops

<table>
<thead>
<tr>
<th>Lingual</th>
<th>Labial</th>
<th>Dental</th>
<th>Alveolar</th>
<th>Palatal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stop</strong></td>
<td><strong>O</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Nasal</strong></td>
<td><strong>ɓ́O ɓO</strong></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.  N|uu contour stops

<table>
<thead>
<tr>
<th>Pulmonic</th>
<th>Labial</th>
<th>Dental</th>
<th>Palatal</th>
<th>Velar</th>
<th>Uvular</th>
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</thead>
<tbody>
<tr>
<td>Affricate</td>
<td>ts</td>
<td>cχ</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Glottalic</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Affricate</td>
<td>̬χ̬'</td>
<td>̬k̬χ̬'</td>
<td>̬q̬χ̬'</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Linguo-pulmonic</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Labial</td>
<td>Dental</td>
<td>Alveolar</td>
<td>Palatal</td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td>Lateral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stop</td>
<td>ʘq</td>
<td>ǀq</td>
<td>ǃq</td>
<td>ǂq</td>
</tr>
<tr>
<td>Affricate</td>
<td>ʘχ</td>
<td>ǀχ</td>
<td>ǃχ</td>
<td>ǂχ</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Linguo-glottalic</th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Affricate</td>
<td>ǀχ'</td>
<td>ǃχ'</td>
<td>ǂχ'</td>
<td></td>
</tr>
</tbody>
</table>

N|uu has a simple five vowel inventory containing /u/, /i/, /o/, /e/, and /a/. However, it also has a large inventory of diphthongs.

3. Methods, data and subjects

I first provide the names of the consultants that I worked with to describe N|uu phonotactic patterns. I then describe the lexical database that I built in order to describe co-occurrence patterns found between consonants and vowels in experiment 1. In the third section, I describe the methodology used in collecting ultrasound data. The ultrasound data is used to describe the articulatory properties of clicks in N|uu, and to investigate the phonetic bases of the Back Vowel Constraint, in experiment 2.

3.1. Subjects

The data presented in this paper comes from fieldwork with speakers of N|uu, the last remaining member of the !Ui branch of the Tuu family, spoken in South Africa. There are less than 10 remaining speakers of this highly endangered language. I worked with a team of linguists: Johanna Brugman, Chris Collins, Levi Namaseb and Bonny Sands. We worked with the following N|uu speakers: Ouma Katrina Esau, Ouma Anna Kassie, Ouma Hanna Koper, Ouma ǀUna Rooi, Ouma Kheis Brou and Ouma Griet.
Seekoei, who speak the Western dialect, and Ouma Hannie Koerant and Oupa Andries Olyn, who speak the Eastern dialect. All of these speakers are bilingual in Afrikaans and N\|uu and are 65-75 years of age. None of the speakers currently resides in a household with other N\|uu speakers, and Afrikaans is their dominant language.

3.2. Lexical Database

The lexical data in this paper comes from a dictionary of N\|uu that is in progress, and is discussed in Sands, Miller and Brugman (2007). Transcriptions were agreed upon by all of the authors. A root database was developed by culling all of the Eastern dialect roots out of the dictionary. These roots were provided by the Eastern dialect speakers (HK and AO), and not known by the Western Dialect speakers. The resulting database contains 790 roots. This paper focuses on the Western dialect of N\|uu, because that is the dialect of most of the remaining speakers. The majority of words have a C_1V_1V_2 or C_1V_1C_2V_2 word structure, though there are a few that have a C_1V_1V_2C_2V_3 word structure. Clicks, including clicks with airstream contours only occur in C_1 position of roots, just as in Ju\'hoansi (Miller-Ockhuizen 2010), !Xôô (Traill 1985) and Khoekhoe (Brugman 2009). Each root was coded for place, manner and airstream of the initial consonant (C_1), height and front/back distinctions on the two vowels in roots (V_1 and V_2), and place, manner and airstream of medial consonants (C_2) in bisyllabic roots. Loan-words that have not yet been assimilated to N\|uu were marked as such in the dictionary and in the database, and they were not included in the lexico-statistical study reported in experiment 1 in Section 4.

3.3. Ultrasound study

Ultrasound investigations were undertaken with four of the N\|uu speakers, and traces in this paper come from Ouma Katrina Esau. Data from other speakers show similar properties. Ultrasound videos were collected using a GE Logiqbook ultrasound machine with an 8C-RS 5-8 MHz pediatric transducer. Head and transducer stabilization were accomplished by using a microphone stand to hold the probe under the chin as in Gick, Bird and
Wilson (2005). The speakers sat on a bench with their heads against the wall as an aid to keep their heads stable.

The acoustic signal was simultaneously recorded with the ultrasound data, using a Shure SM10A head-mounted microphone, and the signal was channelled through a Shure FP23 pre-amp. All ultrasound recordings were made in the frame sentence [na ka] _____ [na ka qo̞ːaːiŋ], meaning ‘I say _____, I say famished’. Tongue traces of clicks are plotted with and discussed relative to the place of articulation of [k] in the first [ka] token and/or the initial [q] in the word [qo̞ːaːiŋ], as in Brugman (2005). Palates were traced from imaging a swallow following the method described in Epstein and Stone (2005). Note that all plots show the position of the tongue relative to the ultrasound probe, not the palate. For discussion of the methodological issues involved in getting from ‘probe space’ to ‘head space’ with ultrasound, see Stone (2005). We recorded 15 tokens of each word (5 repetitions, with 3 tokens per repetition), and the articulatory and acoustic signals were aligned. For each token, a frame was identified immediately before and after the click burst in the acoustic signal. The data presented here was recorded at 50 fps, meaning that we imaged the tongue every 20 ms. With the linguo-pulmonic stops (clicks with airstream contours), frames immediately before and after the pulmonic burst were also identified. The tongue edge was tracked for each of these frames using EdgeTrak software (Li, Khambamettu and Stone 2005). A complete description of the ultrasound setup used in this study, and the methodology used to align acoustic and articulatory data is provided in Miller, Brugman and Sands (2007).

The ultrasound traces provided here are similar to those found for all fifteen tokens produced by all three speakers in terms of the relative constriction locations and shapes, though due to the medium speed of the ultrasound imaging (50 fps) used in this experiment, and the high speed of the tongue in click production, there are significant aliasing effects in the data. The aliasing effects result in considerable variability in the position and shape of the tongue during the frames traced, making it problematic to average across tokens. Therefore, data is only plotted from one token produced by one speaker. However, the relative articulatory patterns found to differentiate the different segments reported here hold true for all of the data.
4. Experiment 1: Database study

In this experiment, I investigate N|uu consonant–vowel co-occurrence patterns. I hypothesize that N|uu plain clicks will pattern similarly to plain clicks found in Ju’hoansi and !Xóõ. Namely, I hypothesize that the dental [ɶ] and palatal [ʃ] clicks will co-occur with both front and back vowels as they do in Ju’hoansi and !Xóõ, while the central alveolar [ɺ] and lateral alveolar [ɺ] clicks will not co-occur with front vowels, but instead will co-occur with a retracted and lowered [ai] allophone of /i/.

Clicks that exhibit airstream contours have never been accounted for in the statement of the BVC in any language. Thus, their phonological patterning is largely unknown. As noted above, Traill (1985) and Ladefoged and Traill (1994) have termed similar clicks in !Xóõ ‘uvular’ clicks, and claimed that these clicks contrast in the posterior place of articulation with so-called ‘velar’ clicks. However, the phonotactic patterning of ‘uvular’ clicks in !Xóõ does not comply with the predicted patterns given in this analysis. If uvular clicks all have posterior uvular releases, this predicts that all of these clicks should not occur with front vowels, similar to uvular pulmonic simple stop patterns. Phonological patterns involving such clicks in Traill’s (1994) !Xóõ dictionary are difficult to interpret. We find words containing both clicks with airstream contours and following back vowels such as ’qahi ‘the hunt’, and words containing the retracted diphthong, such as ’qai ‘bird species’ and ’qai ‘nostril’, which indeed seem to bear out the predictions of Traill’s analysis. (‘ai’ is the orthographic form of the retracted diphthong [ai].) However, we also find words such as ’qhai [qhii] ‘buffalo’, which do not bear out the prediction. The low frequency of clicks with airstream contours in !Xóõ make the interpretation even more difficult.

Based on preliminary investigations of ultrasound data showing that the palatal plain clicks and palatal clicks with airstream contours do not differ in anterior or posterior place of articulation, I hypothesize that N|uu clicks containing airstream contours will fall into two classes similar to those found with the plain clicks. Namely, I hypothesize that the dental and palatal clicks with airstream contours, [ɶ] and [ʃ], will occur freely with front vowels, while the central alveolar and lateral alveolar clicks with airstream contours, [ɺ] and [ɺ], will not occur with front vowels, but will instead co-occur with the retracted diphthong allophone of /i/. This hypothesis is based on the fact that Miller, Brugman et al. (2009) showed
that the posterior place of articulation is the same in [i] and [i̥], and [!] and [ī̥].

While this paper largely addresses the phonological patterning of clicks, pulmonic stop patterns provide further evidence as to the correct analysis of the BVC. As mentioned above, if labial pulmonic stops pattern differently from labial clicks, this rules out an analysis proposed by Traill (1997) in terms of the acoustic feature [acute] vs. [grave]. I hypothesize that the pulmonic stop patterns will be similar to those in Ju’hoansi. Namely, I hypothesize that the labial and velar pulmonic consonants will occur with [i], while the uvular consonants will occur with [ai].

In Section 4.1., I describe the co-occurrence patterns found with consonants and monophthongal front and back vowels. In Section 4.2., I show that the retracted diphthong [ai] is in complimentary distribution with the vowel [i], suggesting that they are both allophones of /i/. Phonation contrasts shown in Tables 2-4, such as voicing, aspiration and glottalization, do not affect the patterning of stops, and neither does nasalization. That is, voiced, aspirated and glottalized stops pattern according to place of articulation, as do nasal stops. Therefore, voiceless unaspirated, voiced unaspirated, voiceless aspirated, voiceless nasal aspirated, voiced nasal, and nasalized glottalized consonants are all grouped together in the tables provided.

4.1. Results: The Back Vowel Constraint in N|uu

4.1.1. Pulmonic and click consonant phonotactic patterns

Figure 2 shows the co-occurrence patterns of front and back vowels with all of the root-initial simple pulmonic stop consonants found in the N|uu root database. Front vowels rarely occur in V1 position of CV1CV2 roots. Therefore, only CVV and CVVCV roots are included in Figure 2. Back vowels are more frequent in the language overall, thus the lower frequency of front vowels across all segment types is reflective of the fact that 89% of roots contain an initial back vowel, while 11% of roots contain an initial front vowel. The alveolar, palatal, and velar initial pulmonic stops co-occur freely with both following front and back vowels, while the labial and uvular pulmonic stops occur only with back vowels.

The low lexical frequency of pulmonic stops in the language, and the particularly low frequency of labial segments, make it difficult to decide
whether the lack of labial stop – front vowel sequences is due to a phonological constraint such as the Back Vowel Constraint, or whether this is just an accidental gap in the root patterns found in the database.

![CVV / CVVCV Roots](chart)

Figure 2. Co-occurrence of initial pulmonic consonants (simple consonants) with following front vs. back vowels in the 790 N|uu root database, CVV and CVVCV roots.

Figure 3 provides the co-occurrence patterns found between click consonants and front vs. back vowels. There are no front vowels in the database following central alveolar [ɨ], lateral alveolar [ɨ], and labial [o] clicks. However, note that labial clicks are low frequency, similar to labial pulmonic consonants, and thus the lack of front vowels following labial clicks could be either due to the Back Vowel Constraint, or be the result of an accidental gap of roots containing both low frequency labial clicks and low frequency initial front vowels.

Due to the ambiguity of patterns found with initial labials, I turn now to medial position, where labial consonants are quite frequent consonants, and high front vowels are also quite frequent. Medial consonant-vowel co-occurrence patterns in N|uu are shown in Figure 4. Crucially, we see that labial consonants occur freely with front vowels in this position. This differs from the lack of labial consonant-front vowel sequences found in CVV roots. Therefore, I attribute the gap of labial consonant – front vowel patterns in CVV roots to the low frequency of each of the sounds.
Figure 3. Co-occurrence of initial click consonants (complex consonants) with following front vs. back vowels in the 790 Niuu root database, CVV or CVVCV roots.

Figure 4. Co-occurrence of medial consonants and following front vs. back vowels in the 790 Niuu root database, CVCV and CVVCV roots.
Alveolar and velar consonants display the same distributional patterns as are found with velar consonants in initial position. There are no sequences of palatal consonants followed by front vowels in the second syllable of N|uu roots.

I attribute this gap to the fact that palatal consonants occur less frequently in medial position, and the fact that bisyllabic roots are less frequent than monosyllabic roots overall (23% of roots are bisyllabic in the database). Therefore, I suggest that it is the low frequency of palatal in C₂ position, and the low frequency of bisyllabic roots, which results in the gap of palatal consonant-[i] sequences in roots in the database.

4.1.2. Phonotactic patterns involving clicks with airstream contours

Figure 5 shows that linguo-pulmonic stops, which are phonetically analogous to those transcribed as ‘uvular’ clicks in !Xóõ, exhibit the same co-occurrence patterns to the complex stops (clicks).

![Figure 5](image)

Figure 5. Co-occurrence of front vs. back vowels with root-initial clicks with airstream contours in N|uu in the 790 Root database, CVV and CVVCV roots.

That is, N|uu dental and palatal clicks with airstream contours, [ǀq] and [ǂq], co-occur freely with front vowels, while labial and alveolar clicks with airstream contours, [ʘq], [ǃq], and [ǁq], do not occur with front vowels,
analogous to their plain click counterparts. I now turn to the investigation of co-occurrence patterns with [i] vs. [ɔi], which show that [ɔi] is an allophone of /i/.

4.2. Results: Allophonic patterns with the diphthong [ɔi]

The BVC patterns with respect to back vs. front vowels are striking, but the diphthong [ɔi] is even more constrained. It is in complementary distribution with the vowel [i]. That is, [ɔi] is an allophone of /i/ that occurs only after the same set of consonants that are limited in their co-occurrence with front vowels, namely [χ], [q], [O], [!, [l], [𝕆q], [!'q], and [lĩ]. Conversely, [i] occurs following labial, coronal and velar pulmonic consonants, as well as the clicks [!] and [i], and the clicks with airstream contours [!’q] and [!’q], as shown in Figure 6. Linguo-pulmonic affricate patterns are not provided here.

There is a maximality constraint in N|uu, which results in a diphthong never occurring in the second syllable of a bisyllabic root. Therefore, medial consonants are not relevant to this pattern.

![Figure 6. Co-occurrence of [i] vs. [ɔi] vowels with N|uu root-initial pulmonic stops, plain clicks and clicks with airstream contours.](image-url)
4.3. Experiment 1: Discussion

I summarize my interpretation of the patterns seen with pulmonic stops, plain clicks, and clicks with airstream contours in Figures 2-5 in Table 5:

Table 5. Summary of C-V co-occurrence patterns in N|uu

<table>
<thead>
<tr>
<th>Pulmonic stops</th>
<th>Occur with front &amp; back V</th>
<th>Occur with back V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clicks</td>
<td>Dental clicks, Labial clicks, Palatal clicks, Uvular, Central and lateral alveolar clicks</td>
<td>Labial clicks, Central and lateral alveolar clicks</td>
</tr>
<tr>
<td>Clicks with airstream contours</td>
<td>Dental clicks, Palatal clicks</td>
<td>Labial clicks, Central and lateral alveolar clicks</td>
</tr>
</tbody>
</table>

These data show that N|uu has a Back Vowel Constraint, similar to that found in Ju|’hoansi (Miller-Ockhuizen 2003) and !Xóõ (Traill 1985). Given the BVC patterns found in N|uu, it is difficult to interpret The Back Vowel Constraint as being due to place of articulation of the anterior constriction. This is because alveolar clicks, which are articulated more forward in the mouth than palatal clicks, do not co-occur with front vowels, while palatal clicks, which have a farther back anterior constriction, do. The N|uu patterns provide further evidence that the acoustic feature [acute] vs. [grave] cannot account for BVC patterns. This is because labial pulmonic stops and labial clicks do not pattern together, and these are both classified as [grave] using Jakobson, Fant and Halle’s acoustic feature. That is, their bursts both have lower frequency energy compared with the alveolar obstruents and palatal and dental clicks. The database results for the clicks with airstream contours show that the dental and palatal clicks of this type, [ǀq], and [ǂq], occur freely with front vowels, while the labial and alveolar clicks of this type, [ʘq], [ǃq], and [ǁq], occur only with back vowels and the retracted diphthong allophone of /i/. The different patterning of dental and palatal plain clicks and clicks with airstream contours, vs. the labial and alveolar plain clicks and clicks with airstream contours, leads me to hypothesize that these clicks may not have a posterior release that is the same across the board. I focus on the posterior constriction because of the patterning of uvular consonants, which are known to retract front vowels cross-linguistically. This hypothesis will be tested in a second experiment using lingual ultrasound imaging, described in section 5.
5. Experiment 2: Ultrasound study

5.1. Introduction

The phonotactic patterns found in experiment 1 with plain clicks and clicks with airstream contours lead me to hypothesize that there are two classes of clicks with respect to their articulatory properties. I hypothesize that the posterior constrictions of the central alveolar [ǃ] and lateral alveolar [ǁ] clicks are similar in location to those found in the alveolar pulmonic consonants [q] and [χ]. Further, the phonotactic patterns seen with the clicks with airstream contours (stops) suggests that these fall into the same two classes, based on the anterior place of articulation. I hypothesize specifically that [ǃː] and [ǁː] will have similar posterior constrictions to those found with [ǃ] and [ǁ]. Moreover, [ǃː] and [ǁː] will have similar posterior constrictions to [ǃ] and [ǁ]. In this experiment, I investigate properties of the posterior constrictions of these four clicks using lingual ultrasound imaging.

5.2. Results

Figure 7 provides ultrasound traces of the tongue in N|uu palatal and alveolar clicks (lingual stops) and clicks with airstream contours (linguo-pulmonic stops). The tongue traces show that the alveolar click, [ǃ], in Figure 7a, involves tongue dorsum and tongue root retraction, which result in a concave tongue body shape, and a convex tongue root shape. The posterior constriction in the alveolar click is at the same location as is found in the uvular pulmonic stop plotted with it. The cavity formed by the tongue body is fairly far forward in the oral cavity, and the anterior constriction is clearly apical. As has been noted by Traill (1985), Ladefoged and Traill (1994), and Thomas-Vilakati (2009), this configuration results in a large lingual cavity.

The production of the palatal click in Figure 7b, [ǁ], involves tongue root raising and a high flat tongue body shape. The posterior constriction of the palatal click is farther back than that of the alveolar click in Figure 7a, and the tongue tip shape is raised and flat. The broad anterior and posterior constrictions give rise to a narrow lingual cavity width and a shallower cavity depth, which results in a smaller overall cavity volume and a flatter tongue body shape. The tongue root proper does not retract, but rather it
Miller raises, as in the articulation of the [u] vowel in English described by Esling (2005). The rarefaction gesture involves gentle tongue centre lowering.

Ultrasound results of the N|uu alveolar and palatal clicks in Figures 7a and 7b show that these clicks exhibit a consistent difference in the posterior constriction locations. The posterior constriction location of the alveolar click, [ǃ], in Figure 7a is in front of the posterior constriction location of the palatal click, [ǂ], seen in Figure 7b.

Figure 7. Ultrasound traces of the tongue in the click closure (solid black), click release (long dashed black), uvular stop (short dashed black), velar stop (dashed grey) and [u] (solid grey), and the palate (solid red) in the N|uu words !uu ‘camelthorn’ (7a: upper left), ūuke ‘fly’ (7b: upper right), !qui ‘ashes’ (7c: lower left), and ñuu ‘neck’ (7d: lower right), (produced in the frame sentence Na ka _____, Na ka qoaqi., I say ___, I say famished. by Speaker Katrina Esau, PCL stands for Posterior Closure Location, and PRL stands for Posterior Release Location).
The posterior closures and releases in the words !ˈqii ‘ashes’ and ǂquu ‘neck’ in Figures 7c and 7d do not differ from the posterior closures in ‘uu camelthorn’ and ǂuuке ‘fly’ seen in Figures 7a and 7b.

The alveolar and palatal clicks also differ in the length and breadth of the anterior and posterior constrictions. In the palatal clicks, both constrictions are long and broad. These contrast with the narrower anterior and posterior constriction shapes found in the alveolar click. The difference in the curvature of the tongue body in the two clicks is more pronounced earlier on, prior to the release of the posterior constriction. In the palatal click, [i], the release of the anterior and posterior constrictions occur more simultaneously. Similar tongue tip, and tongue body shape differences are found among the clicks with airstream contours. The palatal linguo-pulmonic stop (click) in 7d is similar in shape to the plain palatal click in 7b, and the alveolar linguo-pulmonic stop (click) in 7c is similar in shape to the plain alveolar click in 7a.

5.3. Experiment 2: Discussion

Miller-Ockhuizen (2003) analysed the BVC in Juˈhoansi, as involving a [pharyngeal] feature, given the assumed one to one mapping between pharyngeal articulations and tongue root retraction assumed by McCarthy (1994) and Rose (1996). The feature [pharyngeal] was proposed based on the phonotactic patterns seen in that language, with alveolar clicks behaving similarly to uvular consonants. Similar phonotactic patterns have been shown to exist for N|uu clicks in this paper.

The ultrasound data provided in Figure 7 of this paper for N|uu, in Miller, Namaseb and Iskarous (2007) for Khoekhoe, and Miller, Scott, et al. (2009) for Mangetti Dune !Xung, also show that tongue root retraction is not always a property of uvular constrictions, as proposed by McCarthy (1994). However, tongue root retraction and further forward uvular constrictions such as those seen for the alveolar click [ǃ] in Figure 7a, may indeed go together.

Miller, Namaseb and Iskarous (2007) have claimed that the BVC is a phonological consequence of the difficulty of co-producing segments involving incompatible muscular systems, based on ultrasound results of alveolar and palatal clicks in Khoekhoe, and they propose that the tongue body shape differences among clicks account for the BVC patterns.
Thomas-Vilakati (2009) proposes rarefaction gestures for clicks. Further, she shows, via electropalatographic data with 6 speakers, that the rarefaction gestures involved in IsiZulu clicks differ for different clicks. For the IsiZulu dental click, the rarefaction gesture involves tongue centre lowering, and not dorsal retraction, while the IsiZulu palato-alveolar click [ǃ] involves tongue dorsum retraction as well as a greater degree of tongue centre lowering. She notes that the dorsal release is uvular in nature. The lateral click in IsiZulu involves a further back dorsal position, and rarefaction involves mainly tongue centre lowering. Thomas’ EPG data did not provide data on tongue shape, or on the dynamics of the tongue root.

The results of experiment 2 show that the N|uu alveolar click involves both tongue root retraction, and a concave tongue body shape, similar to that found in Khoekhoe. The palatal click, on the other hand, exhibits tongue root raising similar to the vowel [u] in English described by Esling (2005) and the vowel [u] in N|uu seen in Figure 8, and a high flat tongue body shape. These results support my hypothesis that there are articulatory differences in the posterior constrictions of the central alveolar [ǃ] and palatal [ǂ] clicks in N|uu. The concave tongue body shape and tongue root retraction which leads to a convex tongue root shape found with [ǃ], are incompatible with the high flat tongue body shape found with the vowel [i].

Browman and Goldstein’s Articulatory Phonology theory (1989) originally propose that gestures can be produced by one of three relatively independent vocal tract subsystems: oral, velic and laryngeal. Within the oral tract, they propose three relatively independent sets of articulations: lips, tongue / blade, and tongue body. They recognize that tongue root gestures may be eventually needed. Clicks are one such case where the tongue root acts as an independent tongue segment. Further, the data suggest that tongue root shape is important in understanding the articulation of the alveolar click [ǃ]. Thus, I suggest that just as tongue tip is specified for shape, both tongue body and tongue root must also be specified for shape.

The phonotactic patterns seen in experiment 1 led me to hypothesize that the articulation of [ǃ] would be similar to the articulation of [ǃ̟], and that the articulation of [ǂ] would be similar to the articulation of [ǂ̟], in terms of constriction locations and shapes. Results of experiment 2 show that this is indeed the case. The [ǃ̟] click involves tongue root retraction and a concave tongue body shape similar to [ǃ], while the articulation of [ǂ̟] is more similar to [ǂ] in terms of posterior constriction location and tongue body and tongue root shapes. The results refute earlier character-
izations of clicks with airstream contours as involving a uvular posterior release that contrasts with a velar release in the plain clicks. The results show that, rather, both plain and contour clicks have uvular posterior constrictions as shown by Miller, Brugman et al. (2009), and that the clicks differ in terms of their tongue body and tongue root shapes.

6. Phonological model for N|uu clicks

I propose gestural scores for plain alveolar clicks and alveolar clicks exhibiting airstream contours using Browman and Goldstein’s (1989) theory of Articulatory Phonology. The model requires the addition of the tongue root articulator, as well as tongue body shape and tongue root shape, that were not included in the original theory. Distinguishing consonants in Khoesan languages involves describing clicks involving a high flat tongue body shape, [ǂ], and a raised tongue root, as distinct from clicks involving a concave tongue body shape and a convex tongue root shape, such as [ǃ].

I propose two levels of pressure to account for airstream, intra-oral pressure and pharyngeal pressure. This conforms to Mattingly’s (1990) appeal that the basic units of speech should be described in terms of articulatory goals, and mirrors the types of aerodynamic components added to the task dynamics model by McGowan and Saltzman (1995).

I assume, following Zsiga (1997) and Fujimura (2000), that there are distinct phonetic and phonological components of grammar. Thus, I also provide the major phonological features that I propose are specified on the clicks described here. I follow Ladefoged (1982, 1997, 2007) in having an airstream feature. In order to capture the inventory of N|uu airstream contrasts, three airstreams are necessary: pulmonic, lingual and glottalic. All of these airstream contrasts occur as simple segments, and linguo-pulmonic and linguo-glottalic contour segments also exist (Miller et al. 2009). The use of an airstream feature allows me to distinguish between plain clicks that have a shift in airstream at the edge of the consonant, from clicks that I analyse as airstream contour segments, which have a shift at the centre of the segment. I assume that cavity volume is related to tongue shape, and thus does not need to be represented separately.

Figure 8 provides a gestural score of the alveolar click within Articulatory Phonology. The three tongue segments are divided and mapped to prosodic structure: moraic, syllabic and foot structure for the
vowels, and syllable and foot position only for the consonants. The tongue shape specifications are mapped from the articulatory parametric representations. Time points are marked with reference to Thomas-Vilakati's (1999) phases of click production, as well as acoustic landmarks, which aid the reader in seeing the relationship between the articulatory and acoustic properties.

Thomas-Vilakati (1999) describes click articulation with three phases that parallel the phases of pulmonic stops: (A) the tongue dorsum lead phase, where both anterior and posterior constrictions are made in order to form a cavity (this parallels the shutting phase of pulmonic plosives); (B) the overlap phase, where air is rarefied in order to increase the volume of the velaric (lingual) cavity (this parallels the closure phase of pulmonic plosives); and (C) the tongue dorsum lag phase, which includes both the release of the anterior constriction and the release of the posterior constriction (this parallels the release phase of pulmonic plosives). In addition, the Anterior Release of the click is marked with “AR”.

For the alveolar click, the tongue tip raises, forming the constriction at the alveolar ridge, leading to a convex tongue tip shape. The tongue body, which includes the tongue body and dorsum, has a concave shape, with the centre of the tongue body being the lowest point. The tongue root exhibits a convex shape, capturing the fact that the tongue root proper is protruded into the pharynx in the production of the alveolar click.

The first mora of the vowel in the word [ɬəɪ] obtains its tongue shape from the preceding consonant via co-production, and thus there is no tongue root retraction gesture associated with it. The vowel [i] has its own tongue shape, which is high and flat. The tongue root shape is in the neutral position. At the phonological level, these map to place of articulation specifications, in terms of [coronal] and [dorsal] specifications, as well as the feature [RTR], which I would classify as a tongue shape feature.

Airstream is specified at the phonological level, and can be either [pulmonic] or [lingual]. I assume that the [pulmonic] specification is the default specification.

In the palatal click, the tongue body shape is high and flat, and the tongue root shape is neutral, just as in the high front vowel [i]. Thus, there is only a slight co-articulatory effect on a following high front vowel. As noted by Miller, Namaseb and Iskarous (2007) and Miller, Brugman et al. (2009), the muscles found in the articulation of [ɬ] and [i] are compatible, unlike those of [ɬ] and [i]. That is, in a word like ǂii ‘don’t’, there is a gentle lowering effect on the front vowel /i/, which causes it to be realized as [i].
There is not a strong backing effect as is found in the production of [ǃ]. The backward movement of the upper tongue root lowers the tongue body. The tongue root proper is not retracted.

Figure 9 provides a gestural score for the alveolar linguo-pulmonic stop within this model. The tongue tip raises up to make an alveolar constriction just as in the fully lingual alveolar stop during the overlap phase (marked “OL”), but the tongue tip returns to neutral position earlier within the segment at the point marked “AR” for anterior release, which corresponds to the click burst in the spectrogram. We can see that the Tongue Dorsum Lag Phase (“DL”) is much longer in this click than in the fully lingual alveolar stop (capturing the timing differences seen in the waveforms in Figure 1), and there is also a posterior release in this click that is not found in the plain alveolar click. The posterior release is marked “PR”. The tongue root continues returning to neutral position during the vowel following the posterior release, and is responsible for the schwa articulation found in the first mora of the vowel. The lowered F2 and raised F3, as well as the slightly raised F1 seen at the beginning of the vowel in the spectrogram is the result of the lag seen in the tongue root gesture.

This segment is an airstream contour segment, and thus has two timing slots. The first slot is marked for [lingual] airstream, and the second is marked for [pulmonic] airstream. The negative vs. positive intra-oral pressure is marked in the middle panel of Figure 9. At the level of gestures, there is no representation of airflow (though this may need to be captured eventually in something akin to proposals made by McGowan and Saltzman 1995). At this point, I leave it so that the airflow is derived from the particular timing of the individual articulators.

Experiment 2 results showed that the posterior constriction locations in clicks are different for the two classes of clicks presented in Figure 7. Plain alveolar clicks, [ǃ], and alveolar clicks with airstream contours, [ǃ̱], both involve further forward uvular constrictions, while plain palatal clicks, [ǂ], and palatal clicks with airstream contours, [ǂ̱], exhibit farther back uvular constrictions. Note that the consonants that were shown to co-occur freely with front vowels in experiment 1 are farther back than those that are blocked from their occurrence with front vowels, and retract the high front vowel /i/ to [ɨ]. This mirrors the situation with the anterior constriction locations, since the palatal anterior constriction location is farther back than the alveolar one. The results of experiment 2, therefore, show that neither the anterior constriction locations nor the posterior constriction locations can be the phonetic bases of the Back Vowel Constraint in N|uu.
Figure 8. Phonetic and phonological representation of the word !ai ‘belch’. 
Figure 9. Linguistic representation of the word ǃqì ‘be behind’.
Experiment 2 results have shown a contrast in the tongue tip, tongue body and tongue root shapes that are used in the production of the alveolar and palatal clicks, as well as the length of both the anterior and posterior constrictions. Thus, the results support Miller, Namaseb and Iskarous’ (2007) claim that tongue body shape is the phonetic bases of the BVC. They also suggest that the shape of the tongue root may be, in part, responsible for the patterns seen. Tongue root shape is related to the presence of tongue root retraction in the alveolar [!] clicks and the tongue root raising in the palatal [ǂ] clicks.

Posterior place differences are not in themselves contrastive as they are tied to the anterior constriction differences seen in the clicks. However, the place of articulation of the anterior constrictions does not correctly predict the co-occurrence patterns seen. Thus, N|uu BVC patterns show that predictable phonetic differences (e.g. differences in posterior constriction locations in clicks) are phonologically relevant. Since there are two kinds of clicks that have the same posterior constrictions, anterior place differences are also contrastive. Therefore, redundant articulatory properties are relevant to the phonological patterns that these sounds exhibit.

7. Conclusion

I have provided data from co-occurrence of front and back vowels with simple stops (initial pulmonic stops), complex stops (clicks), and contour segments in terms of airstream (linguo-pulmonic stops), as well as medial consonants in the endangered language N|uu. Lexical frequency was calculated over a 790 root database compiled from the N|uu dictionary based on my field-work with a team of linguists. Disparate pulmonic stop and click (lingual stop) patterns show that anterior place of articulation in clicks is not responsible for the co-occurrence restrictions seen between a class of N|uu consonants and front vowels. I have provided ultrasound traces, which show that the posterior constriction locations also do not predict the patterns seen. It is the tongue tip, tongue body and tongue root shapes, which differ among the alveolar and palatal clicks, that act as the phonetic bases of the Back Vowel Constraint. Although most of the articulatory differences found in the tongue body, dorsum and root are predictable from the anterior constriction differences, the tongue dorsum and root differences found among the clicks are phonologically relevant.
That is, I propose that they are the phonetic bases of the Back Vowel Constraint in N|uu, and possibly other KhoeSan languages.

Different places of articulation of the linguo-pulmonic stops do not exhibit differences between the posterior constriction closures and releases that are predicted by Traill’s (1985) and Ladefoged and Maddieson’s (1996) transcription of them. The contrastive element of these clicks is one of timing. They differ in the duration of the tongue dorsum lag phase. As shown by Miller, Brugman and Sands (2007), the release phase of the alveolar click has a duration of about 20 ms, while the release phase of the alveolar click with an airstream contour has a duration of approximately 70 ms. Previously transcribed ‘velar’ clicks are articulated with the lingual airstream, while previously transcribed ‘uvular’ clicks are contour segments, with a lingual closure phase, and a pulmonic release phase.

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