BORA /ɨ/ IS PRODUCED WITH A LOW TONGUE DORSUM AND A DENTAL CONSTRICTION: AN ULTRASOUND STUDY

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ABSTRACT

We present an ultrasound study of the vowels of Bora, an Amazonian language spoken by about 850 people in Peru and Colombia. Bora's phonemic vowels have been traditionally described as /i ɨ ɯ ɛ o a/, where all three high vowels are unrounded, and /ɨ/ and /ɯ/ are very close in F1-F2 space. It has recently been documented that /ɨ/ is produced with lingual-dental contact. Other details of the tongue posture used to produce it have been unknown until now. On the basis of ultrasound recordings of Bora and Spanish words, we find that Bora /ɯ/ is indeed a high back vowel, but /ɨ/ is produced with a low tongue body. Its principal constriction is between the tongue blade and teeth.

Keywords: Bora, dental vowel, ultrasound, vowels, articulatory

1. INTRODUCTION

Bora is a language spoken by about 750 people in Peru and 100 in Colombia. Its phonemic vowels have been described as shown in Table 1, where both /ɨ/ and /ɯ/ are unrounded [1].

Table 1: The vowel inventory of Bora as traditionally described [1]

	front	central	back
high	i	ɨ	ɯ
mid	ɛ		o
low		a	

A contrast between a central and a back vowel which are otherwise identical is theoretically significant since it implies that the binary feature [±back] is too weak to encode all phonological contrasts along the front/back dimension. Previously, Bora vowels have been described in acoustic terms with measurements of F1-F3 based on audio recordings, indicating that /ɨ/ is farther front than /ɯ/ [2]. [3] show that only /o/ is produced with lip rounding and that /ɨ/ is produced with visible contact between the tongue blade and the upper and lower incisors, as shown in Figure 1.

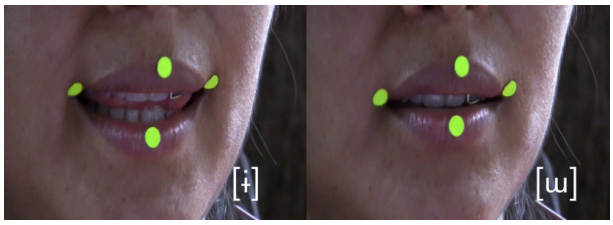


Figure 1: Representative lip/jaw/tongue positions for /ɨ/ and /ɯ/ for one female speaker [3].

This evidence suggests that /i ɨ ɯ/ are not distinguished by lip rounding, but that /ɨ/ is distinguished from the other two by its regular dental contact and apparent lateral airflow. Unlike the apical vowels of Mandarin [4], Bora /ɨ/ is an inherently dental vowel, regardless of context. It is also produced without detectable frication [3]. Its dorsal posture has been undocumented.

2. METHODS

We made recordings of Bora and Spanish words using audio recording and ultrasound video of the tongue. The Spanish /i/ and /u/ provide reference points of prototypical front and back high vowels to compare with the high vowels of Bora.

2.1. Participants

Participants were six native speakers of Bora, aged 25-55 (two female, four male). All speakers were fluent in Spanish as well. Recordings were made in a quiet room at a medical clinic in Iquitos, Peru.

2.2. Materials

Stimuli consisted of 63 Bora words from the dictionary of [5] occurring in the carrier phrase '[tíɲɛ] _____' 'Say _____' as well as 30

Spanish words in the context '[dime] _____' 'Say to me _____'. Phrases were presented up to six at a time, in three predetermined random orders. Each word was presented five times. The Bora recordings were made in a single block first, followed by the Spanish recordings.

2.3. Data collection

Participants wore a Shure Beta 53 head-mounted condenser microphone and an Articulate Instruments UltraFit headset. Audio and lip video were recorded using Articulate Assistant Advanced software (AAA) [6], which was also used to present stimuli orthographically. Since lip positions are relatively well documented for Bora vowels [3], we do not analyze the lip video here.

Lingual ultrasound images were recorded using a GE LOGIQ S8 ultrasound machine with an IC5-9 microconvex transducer via screen capture to a laptop at 60 frames per second. The actual rate of new scans being output by the ultrasound machine was 23 frames per second. The transducer was held in place submentally by the UltraFit headset.

2.4. Data analysis

Audio recordings were force-aligned using the Montreal Forced aligner (MFA) [7]. Spanish was aligned with the Spanish MFA acoustic models [8]. Since no Bora acoustic models exist, we used Kyrgyz models [9], which performed the best among several models we tried based on languages with phoneme inventories similar to Bora's, substituting Kyrgyz phones for Bora before alignment and then back to Bora after alignment. Phone boundaries were corrected manually in Praat [10] after forced alignment.

The screen capture audio was used to synchronize the ultrasound videos with the audio/video recordings using cross-correlation, but only the audio recorded in AAA was used for analysis. Formant frequencies were measured at vowel midpoints using Praat [10]. We note that all of the target vowels are long and most of them have a rising tone, but this does not appear to be accompanied by a change in vowel formant frequencies.

Tongue contours were traced in ultrasound videos in DeepLabCut [11]. We traced the tongue contour in the portions of the videos containing speech using models trained on a diverse set of tongue videos [12]. We then adapted the models to our dataset by relabeling 20 outlier frames per speaker and tracing our images again using the adapted models.

Obvious errors in tongue traces and formant measurements were removed. Tongue traces extracted from vowel midpoints were rotated to make the occlusal plane horizontal and compared using polar Smoothing Spline ANOVA [13, 14, 15] using the `gss` package in R [16, 17].

3. RESULTS

Figure 2 shows the mean acoustic vowel spaces for all six speakers, for all vowels in word-initial position before a labial. This includes the Bora words /iípa/ 'small ash-colored deer', /ɪ́pa/ 'shad fish species' *(sábalo)*, /ɯ́ɯ́pa/ 'species of worm' /ɛ́ɛ́pa/ 'that one (drum, guava, etc.)', /áápa/ 'to be weak or soft (voice/fire)', and /óópa͡kpa/ 'species of monkey', and the Spanish words *iba*, *Eva*, *haba*, *ova*, and *uva*. Bora and Spanish /a/ and /i/ are quite similar in formant frequency, and the Spanish mid vowels are slightly higher than the Bora mid vowels. The Bora vowels /ɨ/ and /ɯ/ are about 1/3 and 2/3 of the way across the top of the F2 vowel space between the /i/s and Spanish /u/, respectively.

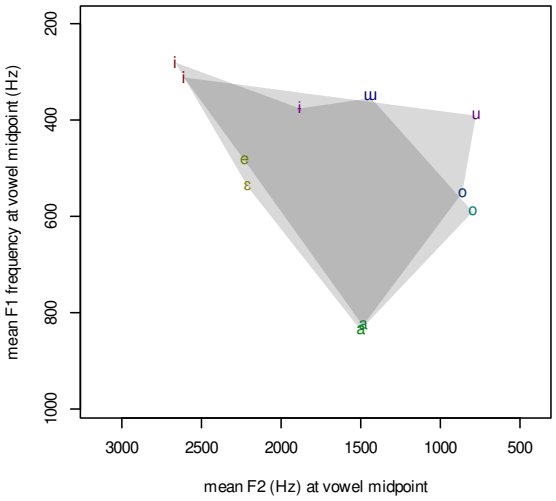
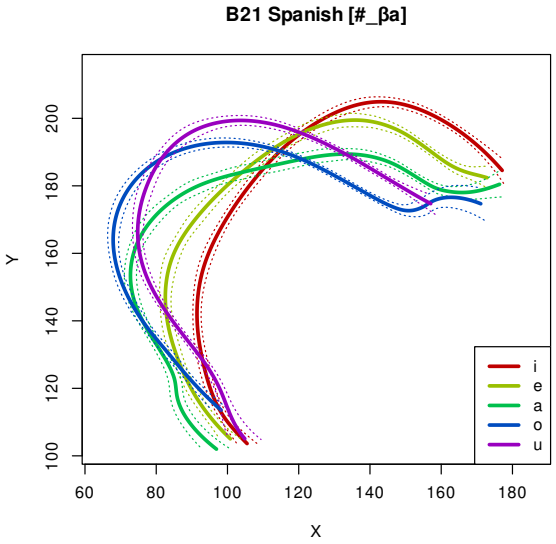


Figure 2: Mean Spanish and Bora acoustic vowel spaces for six speakers. The polygon with /i ɨ ɯ ɛ o a/ is for Bora and the polygon with /i u e o a/ is for Spanish.

Bora /ɨ ɯ/ have been shown not to be distinguished by lip rounding, but rather differ in jaw height and lingual-dental contact [3]. However, the lingual differences between Bora /ɨ ɯ/ and Spanish /u/ (all of which have been described as high non-front vowels) is a major research question which this paper seeks to resolve.

Figure 3 shows sample ultrasound SSANOVA comparisons for one representative male speaker's vowels. Figure 4 shows the same data grouped



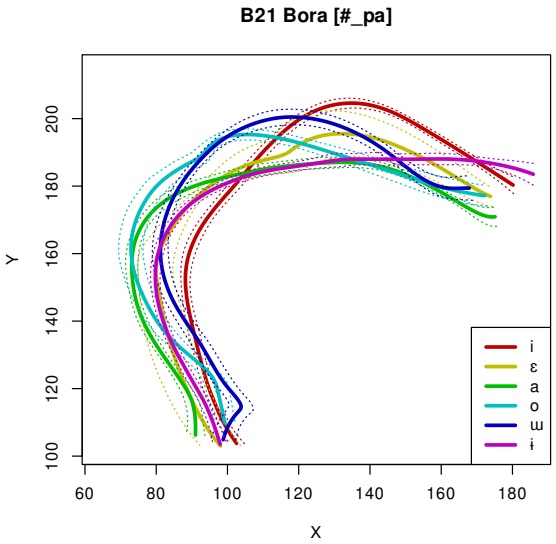
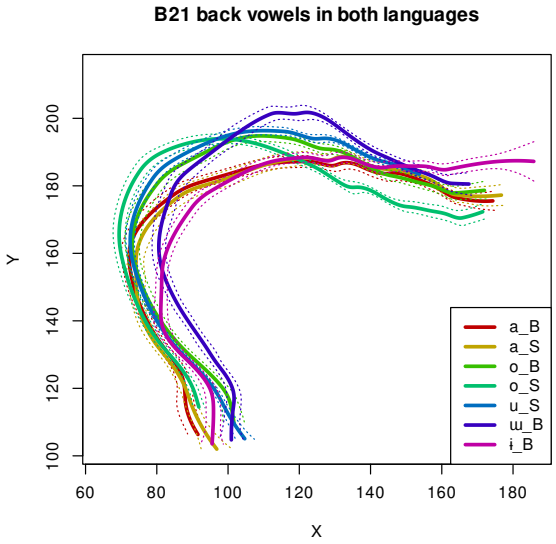


Figure 3: Spanish and Bora SSANOVA comparisons for one male speaker. The tongue tip points to the right.



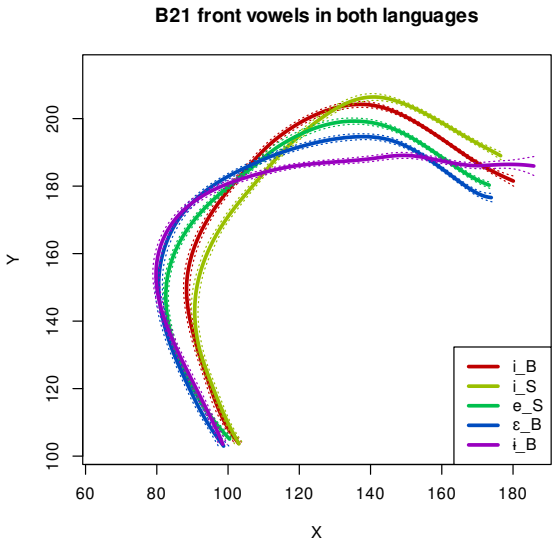


Figure 4: Front and back vowels from both languages for one male speaker. /ɨ/ is included in both sets.

into front and back vowel sets combining both languages, where /ɨ/ is included in both sets. The top panel in Figure 3 shows the expected difference in anteriority between Spanish /i/ and /u/. /e/ has a lower tongue dorsum and more retracted tongue root than /i/. /o/ is produced lower and further back in the vocal tract than /u/, consistent with an upper pharyngeal constriction. /a/ has the lowest tongue dorsum and appears to have its greatest constriction in the lower pharynx, consistent with a low vowel. The bottom panel of Figure 3 shows a similar configuration of five of the Bora vowels /i ɯ o ɛ a/. Surprisingly, the tongue dorsum for the sixth vowel /ɨ/ is as low as for /a/. The blade of the tongue is higher for /ɨ/ than for any of the other vowels, consistent with this vowel having a dental constriction that the others lack.

Figure 4 directly compares the front and back vowels across languages. /ɨ/ is included in both sets since its status is arguable, and the main focus of this study. The top panel shows that the Spanish /u/ in *uva* is articulated more posteriorly than the Bora /ɯ/ in /ɯúpa/. That is, although Bora /ɯ/ exhibits a higher F2 than Spanish /u/, this is not just due to /ɯ/ being unrounded; it is also a more central vowel for this speaker (and three of the other five). The /o/s in both languages are very similar, with interspeaker variation in which is more retracted (posterior). Bora and Spanish /a/ appear identical. For four of the six speakers, Bora /ɯ/ is central in relation to the Spanish back vowel /u/ (as seen for speaker B21 in Figure 4). For the other three (B7,

and B8), the tongue positions for the two vowels are similar, and the observed acoustic difference is likely due primarily to lip rounding in /u/, which lowers F2. For five of the six speakers, Bora /o/ is higher than Bora /a/ (as seen for B21). For one speaker (B7), the tongue positions for these vowels are very similar, suggesting that they are distinguished primarily by lip rounding.

The bottom panel of Figure 4 shows that Spanish /i/ in *iba* is the highest of the front vowels, followed by Bora /i/ (/iípa/), Spanish /e/ (*Eva*), and then Bora /ɛ/ (/ɛɛ́pa/). Bora /ɨ/ is lower than all of the back vowels and virtually all of the front vowels in both languages. The tongue root position for /ɨ/ is similar to the high back/central /u ɯ/ and the mid front /e ɛ/. The tongue height hierarchy observed for B21 is replicated to some extent by the other five speakers, as summarized in Table 2.

Table 2: Tongue front height hierarchies among front vowels for all six speakers. Bora front vowels are shown as /i_B ɛ ɨ/ and Spanish front vowels are shown as /i_S e/

speaker	front vowel height hierarchy
B2	i_S > i_B > e > ɛ > ɨ
B21	i_S > i_B > e > ɛ > ɨ
B20	i_S > i_B > e = ɛ > ɨ
B1	$i_S = i_B$ > e > ɛ > ɨ
B8	i_B > ɛ > i_S = e = ɨ
B7	i_S = e > i_B > ɨ > ɛ

All six speakers show a higher tongue blade for /ɨ/ than for any of the other vowels. In addition, four of the six speakers show significant raising/retraction of the tongue dorsum in /ɨ/, higher than in any of the other front vowels. B21 shows a similar shape that is not significantly higher than /ɛ e/, and B20 has no difference in posterior tongue dorsum height between /ɨ ɛ e/.

4. DISCUSSION

In terms of formant values, Bora's /ɨ/ and /ɯ/ are acoustically intermediate between /i/ and Spanish /u/. /ɨ/ and /ɯ/ both have low F1 frequencies consistent with high vowels, and intermediate F2 frequencies. With respect to /ɯ/, the explanation for its observed acoustic properties is straightforward: since it is produced with unrounded lips [3], it has somewhat higher F2 than Spanish /u/, regardless of whether it is produced with a constriction location similar to /u/ or with a somewhat more anterior constriction. Both types of articulations are observed in our data.

/ɨ/ is articulated with a very low tongue body, typically lower than for the high vowels /i/ and /ɯ/ and typically also lower than the Spanish /e/ and/or Bora /ɛ/. Although the tongue body is low for /ɨ/, the tongue blade is raised, which is consistent with the previously observed lingual-dental contact illustrated in the left panel of Figure 1. The previously analyzed video data have indicated central dental contact and lateral airflow for /ɨ/ [3]. For many of the speakers, /ɨ/ could be characterized as /ɛ/ with tongue blade raising. [18]'s reconstruction posits that Bora /ɨ/ is a reflex of Proto-Bora-Muinane /*e/, suggesting that this vowel underwent a change of dentalization rather than raising and retraction. The raised/retracted tongue dorsum is consistent with a lateral sonorant (expanding the tongue in the mid-sagittal plane as it narrows laterally). Tongue dorsum retraction is also consistent just with a dental articulation, since narrowing the tongue laterally is one way to achieve tongue blade fronting.

Given that /ɨ/ is produced with such a low tongue dorsum, it is potentially surprising that it has such a low F1 and has been classified on this basis as a high vowel. F1 in high vowels is typically a Helmholz resonance of the back cavity and the tongue passage. For Bora /ɨ/, the entire pharynx and oral cavity constitute the back cavity, and the passages around the sides of the tongue blade constitute the neck(s) of the Helmholz resonator. [19] describes such a configuration for the prototypical front rounded vowel [y], where the tongue passage and lip constriction form a single narrow tube, without any front cavity.

5. CONCLUSION

Ultrasound images of Bora vowels confirm that /ɯ/ is a high back or central vowel, whereas /ɨ/ is produced with a very low tongue body, meaning that its primary constriction is between the tongue blade and the teeth. It may still be considered a high vowel in acoustic terms, but articulatorily its status as a high vowel depends on how vowel height is defined. In terms of the relationship between the tongue dorsum and the palate, /ɨ/ is a low front vowel, but in terms of the relationship between the tongue blade and teeth, it is a high super-front (dental) vowel. This finding is consistent with the conclusions in [3], who additionally present phonological evidence demonstrating that /ɨ/ patterns in Bora as a front vowel which is not quite as high as /i/.

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