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[ATR] feature involves a distinct tongue root articulation: Evidence from ultrasound imaging

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Abstract

The feature [ATR] (Advanced Tongue Root) assumes a unique role of the tongue root in the production of [±ATR] vowels. However, whether the actual position of the tongue root accurately characterises vowel pairs distinguished by this feature has attracted some controversy. This paper tests the hypothesis that the [ATR] specification of a vowel maps onto a definite articulatory position of the tongue root. It further investigates whether such a mapping reflects which of the values of [ATR] is dominant in a language. The results of five ultrasound imaging experiments using Dagbani, a Gur language of Ghana, show that [+ATR] vowels of all height specifications are produced with a more anterior tongue root than [−ATR] vowels. They also show that tongue body height, a plausible alternative to tongue root position, does not consistently define the distinction. More importantly, the results show that vowels specified for [+ATR], the dominant value in Dagbani, are produced with a tongue root anterior displacement from a neutral position while the recessive [−ATR] vowels have variable tongue root positions. The results support a direct mapping between the phonological feature [ATR] and the articulatory gestures producing it.

Keywords: Vowel harmony; [ATR]; Phonetics–phonology interface; Ultrasound imaging; Dagbani

1. Introduction

In phonological analyses of tongue root harmony, it is generally assumed that the relevant phonological feature distinguishing the vowels in each of the pairs i/ɪ, u/ʊ, e/ɛ, o/ɔ, and ə/a is [ATR] (Advanced Tongue Root), and that the vowels are distinguished by a tongue root gesture (see Casali, 2003, 2008 for extensive review). The first and second vowel in each pair are assumed to be [+ATR] and [−ATR] respectively. The vowels are grouped into two classes, shown in (1), while the featural distinctions between them are investigated.[1]

(1)

Class I vowels			Class II vowels		
i		u	ɪ		ʊ
e		o	ɛ		ɔ
	ə			a	

While the [ATR] assumption has been made in previous research on Dagbani (Dakubu, 1997; Olawsky, 1999; Hudu, 2013), no experimental study supports the view that Dagbani vowels are distinguished by a tongue root gesture. Given

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[1] In Dagbani, the [−ATR] variant of [i] is not [ɪ] but [ɨ], unlike the general representation in (1) (see Hudu (2010, 2013) for a detailed discussion). In this paper, discussions focusing solely on Dagbani make reference to [ɨ].

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that vowels in each pair typically differ in their first formant values (e.g. Hess, 1992), an assumption that they are distinguished phonetically by a tongue body gesture is quite conceivable. Two main hypotheses are tested in this study.

(2) **Hypothesis A**: Tongue root features have distinct articulatory tongue root positions (the Tongue Root Gesture Hypothesis)
Hypothesis B: The mapping between a lingual feature and articulatory gestures reflects which value of the feature is dominant in a language (the Direct Mapping Hypothesis).

Previous articulatory studies of tongue root harmony systems (e.g. Ladefoged, 1968; Lindau, 1975, 1979; Tiede, 1996; Whalen and Gick, 2001; Gick et al., 2006) support the Tongue Root Gesture Hypothesis, the prevailing assumption being that tongue root position is a major articulatory property that distinguishes vowels in each pair. While the present study is the first to test these hypotheses using Dagbani, some of the issues addressed under the Tongue Root Gesture Hypothesis have been addressed in previous experimental studies, reviewed shortly below. Lindau (1979) and Tiede (1996) in particular have shown that the position of the tongue root is part of the expansion of the pharynx in the production of Class I vowels, giving them a larger pharyngeal volume than Class II vowels. However, results of past studies do not give any indication whether the position of the tongue root for vowels in either class depends on what the dominant tongue root feature is.[2] This question is addressed in the present study, with a focus on Dagbani, a language with a phonologically active Class I feature.

Research on the Dagbani vowel phonology (e.g. Hudu, 2010, 2013) show that underlying Class II vowels surface as Class I in a harmonic domain, with an underlying Class I vowel /i/ spreading the [+ATR] harmonic feature. Class I vowels surfacing in this harmonic pattern, discussed further in section 1.2, are referred to here as harmonic Class I vowels. Class II vowels also surface as Class I in other phonological contexts not driven by harmony. These are labeled non-harmonic Class I vowels. The Tongue Root Gesture Hypothesis addresses two fundamental questions on Dagbani [ATR] feature specifications. The first question regards whether tongue root position defines the distinction between Class II vowels and non-harmonic Class I vowels; the second examines whether it defines the distinction between Class II vowels and harmonic Class I vowels. In answering both questions, the hypothesis considers the alternative prediction that tongue body height, rather than tongue root position is the primary articulatory correlate of the feature distinguishing vowels in the two classes. The second question also determines whether the emergence of harmonic Class I vowels is phonological or merely co-articulatory. If the emergence of harmonic Class I variants is a phonological process, these vowels are expected to have the same tongue root position as non-harmonic Class I vowels. If it is a result of phonetic interpolation, harmonic Class I vowels may be significantly and consistently less advanced than non-harmonic ones.

While these peculiar issues about Dagbani [ATR] harmony system requires different tests to investigate the Tongue Root Gesture Hypothesis, testing the Direct Mapping Hypothesis requires a more straightforward comparison of the tongue root positions of vowels in the two classes to a neutral position to determine if indeed the mapping is a direct one. These questions, tests and sub-tests are elaborated further in section 1.3. In the next section, previous studies on the phonetics of tongue root features are reviewed. Section 1.2 presents a sketch of aspects of Dagbani vowel harmony that bear on the questions investigated here, while the general methodology used in all the experiments is presented in section 2. The experiments testing the hypotheses are reported in sections 3–7.

1.1. Articulatory correlates of lingual features

There are two broad views on the mapping between lingual features such as [ATR] and the articulatory properties of the tongue. One views the mapping as a direct one, arguing that vowels that show a phonological [ATR] feature have a unique tongue root gesture or pharyngeal cavity volume (e.g. Parkinson, 1996; Tiede, 1996; Gick et al., 2006). This view is supported by results of X-ray, MRI and ultrasound studies, discussed further shortly. The results of studies on Ateso (Lindau, 1975; Lindau and Ladefoged, 1986), on the other hand, form the basis for Hyman's (1988) argument that the mapping between the feature and the gesture is an indirect one. Hyman's argument is based on the observation that while Ateso vowels belonging to these two classes seem to show a harmony pattern comparable to other ATR systems in Nilotic, the main articulatory difference between Class I and Class II vowels in Ateso is tongue height adjustment, not tongue root articulation.

Apparent exceptions such as those observed in Ateso raise questions regarding the accuracy of past descriptions of some languages with lingual harmony. While [ATR] has been used to describe many languages with lingual harmony, some of these descriptions may not be accurate because the articulatory distinction between the vowels may not be based on tongue root articulation. Even in languages that show active tongue root distinction, the use of the feature [ATR] has been shown to not always be accurate, especially in studies that claim a universally dominant [+ATR] feature (see for instance Hulst and Weijer, 1995; Polgárdi, 1998; Baković, 2000). Studies on Yoruba and Wolof (Archangeli and Pulleyblank, 1989,

[2] Although see Allen et al. (2013) on Yoruba, which tests these hypotheses following the results of the present study (as reported in an earlier draft of this paper).

1994; Pulleyblank and Turkel, 1996; Pulleyblank, 1996; Allen et al., 2013) and Ogori (Salting, 1998) show that these three languages have a dominant [−ATR]/[RTR] feature (see Archangeli and Pulleyblank, 1994, for further discussion). Li (1996) has also argued that the dominant tongue root feature in the canonical vowel harmony pattern of Tungusic is [RTR], while Noske (2000) shows that both [ATR] and [RTR] are active in Turkana. Casali (2003, 2008) also argues, based on the results of a survey of many Niger-Congo and Nilo Saharan languages, that the dominant tongue root feature of a language fundamentally depends on the structure of its vowel inventory: [+ATR] is dominant in languages that show [ATR] contrast among high vowels while [−ATR]/[RTR] is dominant in languages with [ATR] contrast restricted to non-high vowels.

Results of experimental studies largely support the direct mapping view. X-ray studies of Igbo (Ladefoged, 1968) and Akan (Lindau, 1979) show tongue root position as the articulatory property distinguishing vowels in the two classes. Class I vowels in these languages display a more anterior tongue root position than Class II vowels. Lindau (1979) also reports a distinction in larynx height for Akan vowels, with Class I vowels displaying anterior tongue root position and a lowered larynx and Class II lacking both gestures. Results of MRI study of Akan (Tiede, 1996) further show that compared to Class II vowels, Akan Class I vowels have a larger tongue root advancement and a lower larynx height in the sagittal dimension, and a larger pharyngeal airspace in the lateral dimension. The results thus suggest that control in both dimensions is equally important in producing vowel contrasts in Akan.

Other recent studies (e.g. Whalen and Gick, 2001; Namdaran, 2006; Gick et al., 2006; Miller et al., 2007, 2009; Miller, 2008; Hudu, 2008) have used ultrasound imaging to investigate tongue root-related phonological issues. Whalen and Gick (2001) find an interaction of tongue root position and tongue body height with intrinsic fundamental frequency effects in the ATR systems of both Igbo (Nigeria) and Kinande (Democratic Republic of Congo). Gick et al. (2006) observe a systematic variation in tongue root position across vowels in Kinande, with tongue root position for vowels in Class I significantly more anterior than their Class II variants. However, these results do not address the question whether the tongue root is the primary articulatory gesture distinguishing vowels in the two classes. Hypothesis A addresses this by testing tongue body height as a plausible primary phonetic gesture distinguishing vowels in the two classes. The results are also not affected by whether a language has a dominant [+ATR] or [−ATR] value. This is investigated under Hypothesis B, the Direct Mapping Hypothesis.

1.2. Dagbani vowel harmony

It is shown in previous studies of Dagbani (e.g. Hudu, 2010, 2013) that [+ATR] is the dominant harmonic value of [ATR]. The [−ATR] value is recessive in the sense that [−ATR] vowels neither trigger nor block any phonological process. These studies also establish two degrees of assimilation in Dagbani lingual harmony. One is an impressionistically complete assimilation of the target to the trigger in two harmonic contexts: (i) when the trigger is /i/ and the target is /ɨ/, and (ii) when trigger and targets are mid vowels agreeing in rounding. The pairs in (3) illustrate a complete assimilation of /ɨ/ to /i/. With a Class II root vowel, the non-root vowel surfaces as [ɨ], while underlying suffixal or clitic /ɨ/ surfaces as [i] in a harmonic span triggered by a root /i/.

(3) Underlying /ɨ/ as the target of ATR harmony

	Class II roots		Root-to-affix Class I harmony	
a.	bɨ́n-ɨ̂	'a thing'	pín-î	'a gift'
b.	tʊ̀ʔ-ɨ̀	'join'	díʔ-í	'a mirror'
c.	dɔ́lɨ́-bʊ̂	'following'	dí-hí-bû	'feeding'
d.	kpáb-ɨ́	'carry on the back'	kpìb-î	'lice'
e.	bɔ́hɨ́ tɨ́	'ask us'	lìhì tí	'look at us'
f.	o dà mɨ̂	'he bought'	o mì mî	'he knows'

The second context is shown in (4), with a trigger and target that are both mid vowels, the final vowel being the harmonic trigger.

(4) Mid vowel target

	Class II roots		Affix-to-root Class I harmony	
a.	mɔ́l-ɨ̂	'announce'	mòl-ô	'an announcement'
b.	dɔ́r-tɨ́	'diseases'	dór-ó	'a disease'
c.	bɛ́-hɨ̂	'shins'	bé-ê	'a shin'
d.	dɛ́m-bʊ̂	'playing'	dèm ó	'play with him/her'
e.	ʃɛ́-hɨ́	waist	ʃé-é	'a waist'

The second degree of harmony has mid vowel triggers and low vowel targets, illustrated by the word pairs in (5). Impressionistically, /a/ is raised before a domain-final [o], but it is not obvious exactly what articulatory property of /a/

changes in this context. The perceived raising suggests that the change affects tongue body height. However, similar acoustic effects are expected whether the primary gestural change affects the tongue root or the tongue body.

(5) Mid vowel trigger, low vowel target

	Underlying Class II roots		Affix-to-root Class I harmony	
a.	kál-tɨ́	'doors'	kə́l-ó	'a door'
b.	pál-lɨ́	'a new one'	pə́l-ó	'a new one (animate).'
c.	tàdáb-tɨ̂	'writing inks'	tədə́b-ô	'a writing ink'
d.	tàtáb-tɨ̂	'look-alike-pl.'	tətə́b-ô	'a look-alike'
e.	gár-tɨ́	'beds'	gə́r-ó	'a bed'

In addition to the question whether the harmonic feature is phonetically realised as tongue root advancement, as opposed to tongue body height, a more fundamental question is whether the featural change is phonological.

1.3. Hypotheses

1.3.1. Hypothesis A: the Tongue Root Gesture Hypothesis

Given the phonology of Dagbani [+ATR] vowels, the Tongue Root Gesture Hypothesis has two sub-hypotheses:

1. Non-harmonic [ATR] Hypothesis: tongue root position is the primary distinction between Class II vowels and non-harmonic Class I vowels.
2. Harmonic [ATR] Hypothesis: tongue root position is the primary distinction between Class II vowels and harmonic Class I vowels.

The Non-harmonic [ATR] Hypothesis predicts that each non-harmonic [+ATR] vowel is produced with a tongue root position that is anterior, compared to its [−ATR] variant. It also predicts that this difference is greater than any other articulatory difference such as tongue body height. A significant difference in both tongue root and tongue body positions is not ruled out regardless of whether a tongue root or a tongue body gesture primarily distinguishes vowels in the two classes. This is because being a muscular hydrostat with a fixed incompressible volume (Kier and Smith, 1985) any change in the shape or position of one part of tongue affects that of another (Stone and Lundberg, 1996; Hironori, 2001; Hiiemae and Palmer, 2003, etc.). If the distinction is based on tongue root, any change in the position of the tongue root will affect tongue body height. If it is a height distinction, the acoustic or perceptual F1 decrease that characterises Class I vowels may result in a higher tongue body and a more anterior tongue root. Thus in answering the question whether the active phonological feature is based on a unique tongue body height or tongue root gesture, one of three possible outcomes is expected:

1. a difference in both tongue root and tongue body positions, with tongue body difference secondary to tongue root difference,
2. a difference in both tongue root and tongue body positions, with tongue root difference secondary to tongue body difference, and
3. a difference in both tongue root and tongue body positions, with neither secondary to the other.

The first outcome is predicted under Hypothesis A. Across all vowels for each speaker, the tongue root is expected to show more significant and consistent differences compared to the tongue body. The second and third outcomes are inconsistent with the hypothesis that [ATR] is the main feature distinguishing vowels in the two classes, with height being enhanced by or secondary to tongue root difference. The Non-harmonic [ATR] Hypothesis is tested in Experiment 1.

The Harmonic [ATR] Hypothesis, tested in Experiment 2, also predicts an anterior tongue root gesture for harmonic [+ATR] vowels and a difference in tongue root gestures that is greater than tongue body height. Two subtests are carried out to determine if the assimilation observed in harmonic contexts is phonological. The first subtest compares results of experiments 1 and 2 to determine if the assimilation in harmonic contexts is neutralising. If the assimilation in harmonic contexts leads to a phonological neutralisation between underlying [−ATR] targets and [+ATR] triggers, little or no difference between the tongue root position of harmonic and that of non-harmonic Class I vowels is expected. If the assimilation is merely co-articulatory, the tongue root position is expected to be less anterior for putatively [+ATR] vowels in harmonic contexts than non-harmonic [+ATR] vowels. This is tested in Experiment 3.

The second subtest investigates whether the level of assimilation is affected by the relative distance between the trigger and target. It does so by comparing the tongue root gesture of the first to that of the second vowel in a three-syllable word with a domain-final harmonic trigger (see 5d). A lack of distance effect will strengthen the conclusion that the assimilatory pattern observed in Dagbani is an instance of vowel harmony. This is tested in Experiment 4.

1.3.2. Hypothesis B: the Direct Mapping Hypothesis

The Direct Mapping Hypothesis says that in a language with a lingual harmony (e.g. [ATR], [RTR], [High]) there is a direct mapping between the phonologically active lingual harmonic feature and the position of the relevant part of the tongue. In other words, the dominant harmonic feature of a language with lingual harmony has a unique articulatory correlate independent of the recessive feature. Applied to the feature [ATR], the hypothesis says that the tongue root has a unique and predictable gesture in the production of vowels specified for the dominant value of [ATR]. By contrast, the recessive value lacks any unique gesture.

In order to investigate this, it is important to establish a baseline from which the tongue root position of the dominant and recessive values of the feature can be measured. In this regard, studies (e.g. Honikman, 1964; Laver, 1978; Jenner, 2001; Gick et al., 2004; Wilson, 2006) have shown that there is an underlying or default position for articulators specific to every language. In Gick et al. (2004) and Wilson (2006), this default position is linked to the speech rest position or inter-speech posture (ISP), the motionless position of the articulators during inter-utterance pauses. The ISP is used in previous ultrasound studies of lingual features such as Namdaran (2006) and Hudu et al. (2009). Following these studies, the ISP is taken as the relevant neutral baseline position from which measurements of advanced and retracted positions of the tongue root are made.

The Direct Mapping Hypothesis predicts that for a language in which the distinction between vowels in the two classes is based on a tongue root gesture, the dominant harmonic feature value has a distinct articulatory position compared to the tongue root neutral position. Assuming that α is the ISP of the tongue root, β is tongue root position for [+ATR] vowels, and γ is its position for [−ATR] vowels; the hypothesis makes three predictions on the tongue root position for vowels of different values of [ATR] in three language types:

1. For a language Type A with a dominant [+ATR] (e.g. Dagbani and Kinande), β is predicted to be significantly and consistently anterior to α, and γ to conform closely to α.
2. For a language Type B with a dominant [+RTR] (e.g. Yoruba and Tungusic), γ is predicted to be significantly and consistently posterior to α and β to conform closely to α.
3. For a language Type C with both active [+ATR] and [−ATR] (e.g. Turkana), a significantly anterior position for β compared to α and posterior position for γ compared to α are predicted. The difference between α and β is not expected to be any greater than that between α and γ.

A common prediction for language types A and B is that, a phonologically inactive feature value is generally not expected to correspond to a distinct tongue root position. For a language Type A, [−ATR] vowels could have the same tongue root position as the ISP. But they could also be anterior or posterior to the ISP. For a language Type B, [−RTR] vowels could have a tongue root position that is posterior or anterior to the ISP, or one that is not different from the neutral position. It is also possible that distinct gestures may be assigned to the opposite values of [ATR] and [RTR] in order to enhance the contrast between them. Such a contrast enhancement mechanism could result in a consistently posterior tongue root position for [−ATR] vowels in a language Type A or anterior position for [−RTR] vowels in a language Type B. A language (Type A or B) with such an enhancement mechanism may not be different articulatorily from the predictions for language Type C. What is important in all cases is that a dominant feature displays a tongue root position that consistently and significantly differs from the neutral position in a predicted direction.

On the contrary, if there is no correlation between the dominant harmonic feature of a language and the articulatory position of the tongue root, and assuming that there are indeed different tongue root positions for vowels in the two classes as found in previous studies of other languages (and tested under the Tongue Root Gesture Hypothesis), both β and γ could maintain a position posterior to α for a language Type A or anterior (to α) for language Type B. Either result will also be inconsistent with the prediction for a language Type C. The present study only tests language Type A, using Dagbani.[3] The test is shown in Experiment 5. Table 1 shows a summary of the hypotheses, tests, predictions and the experiments specific to Dagbani.

2. General methodology

2.1. Participants

Five adult male native speakers of Dagbani between the ages of 27 and 45 participated in the study. All participants grew up in Tamale, Ghana, speak the Western Dialect of Dagbani, and happened to be the only speakers within reach in

[3] The formulation and predictions of the hypothesis thus assumes a language-specific privative interpretation of [ATR] (Troubetzkoy, 1939; Pulleyblank, 1995, etc.) by which [ATR] can be privative in some languages, as in types A and B, but equipollent in others as in Type C.

Table 1
Summary of hypotheses, tests and predictions.

Hypothesis A			
Sub-hypothesis	Sub-test	Prediction	Experiment
Non-harmonic [ATR]		Differences in both tongue root position and tongue body height for non-harmonic [+ATR] vowels; tongue body height secondary to tongue root position.	1
Harmonic [ATR]	Main test	Differences in both tongue root position and tongue body height for harmonic [+ATR] vowels; tongue body height secondary to tongue root position.	2
	Degree of assimilation	Same tongue root position for harmonic and non-harmonic vowels.	3
	Distance effects	Same tongue root position for near target and far target vowels.	4

Hypothesis B	
Prediction	Experiment
Tongue root of [+ATR] vowels anterior to ISP; tongue root of [−ATR] vowels lacks a definite position.	5

Canada. Pre-experimentally, the data were based mainly on my intuitions as a native speaker of the Eastern Dialect. Participant AIM was recorded in a quiet home in Mississauga, Ontario; IZD was recorded in the phonetics laboratory of the University of Victoria, while AAB, AB, and HS were recorded in their private homes in Ottawa.

2.2. Procedure

The recordings in Mississauga and Victoria were done using a GE Logiqbook E portable ultrasound machine with an 8C-RS 5-8 MHz transducer. In Ottawa, a Sonosite Titan High-resolution portable ultrasound machine with a C11/8-5 MHz transducer was used because at the time of the recordings, the GE Logiqbook ultrasound machine was not available. All recordings were done at a standard rate of 29.97 frames per second (about 33 Hz).

The ultrasound transducer was set under the chin to image the entire mid sagittal region. Ultrasound gel was applied to the head of the transducer and participants also drank water before the start of each recording session, both measures meant to enhance the clarity of the ultrasound image. To maintain its stability, the transducer was held by an adjustable microphone boom mounted on a table in front of the speaker. Real time ultrasound video was transmitted using SVGA cable and recorded directly onto a laptop computer using Adobe Premier Pro, via a Canopus audio–video mixer. Audio recording was done simultaneously using a head-mounted microphone connected to the Canopus via a Shure dual microphone pre-amplifier.

Further measures to ensure accuracy in the data collection process included the use of a back rest to restrain head movement and a clamp to fasten the microphone boom stand to the table. In Mississauga, and Ottawa, where there was no standard laboratory chair, a back rest with adjustable head rest was constructed using a wooden board placed vertically on the seat of a chair and fastened to the original back rest of the chair. The recordings were visually monitored. If the transducer or participant's head was observed to have moved, the recording was repeated. Words containing target vowels were embedded in a carrier phrase, shown in (6).

(6) *bɔ̀lɨ̀-mɨ̀* __ *tɨ́* *má*
say-imperative __ give 1sg.object
'say __ for me'

The stimuli for the first two experiments (see below) were mixed in a random order to ensure that they served as distractors to each other. Additional distractor words were added. In Mississauga, participants were presented with the stimuli and their English translations; in Victoria and Ottawa, they were presented with only the English translations of the stimuli. Because there is no standard orthography for Dagbani acceptable to all speakers, the stimuli and distractors were shown to each participant to ensure that he was comfortable with the spelling and translation of each word prior to the start of the recordings. In all recordings, each word was shown in a presentation slide directly facing the participant. Target vowels were repeated in 5 blocks with 4 or 5 repetitions in each block, producing a maximum of 25 tokens of each vowel. This maximum number of tokens was randomly extracted for [ɨ] and the ISP. For some subjects, there were fewer tokens for some of the vowels as some frames were discarded because they did not show a clear image of the tongue. The mid-point frame of each target vowel token was extracted from the video as a still image and measured for the statistical tests.

3. Experiment 1: Testing the Non-harmonic [ATR] Hypothesis

3.1. Introduction

This experiment tests the hypothesis that Class II vowels and non-harmonic Class I vowels have different tongue root positions. The stimuli, (7), do not include the low vowel pair [a/ə] because [ə] is derived only in harmonic contexts. The tone marks in (7) and subsequent data reflect the tones the vowels bear when embedded in the carrier phrase.

(7) Stimuli for non-harmonic advanced vowels and retracted vowels

	Advanced vowels		Retracted vowels	
a.	tí	'vomit'	tɪ̀ má	'for me
b.	tú	'insult'	tʊ́ m	'work'
c.	tó	'bitter'	tɔ́ m	'bitterness'
d.	té	'filter'	dɛ́ m	'play'

Class I vowels alternate with their [−ATR] variants in CV position. In this context, non-low Class II vowels do not surface, as the CV forms in (7) show. However, this alternation is not driven by vowel harmony. The data in (7) show the exact stimuli used for the recording in Victoria and Ottawa. In Mississauga, where the first recording took place, the [−ATR] vowels [ʊ, ɔ, ɛ] appeared in the words *tʊ́l-lɪ́* 'hot-sg.', *tɔ́-lɪ́* 'mortar-sg.', and *tɛ́lɪ́* 'to flood'.

3.2. Methods

All measurements were done using the image measuring software ImageJ (Rasband, 1997) (http://rsb.info.nih.gov/ij/). With the transducer mid point serving as the base for determining tongue root and tongue body distances, a straight measurement line was drawn to the tongue root and tongue body positions on the midsagittal arc at a specified angle for each vowel pair. The length of the measurement line, displayed in pixels, was recorded and later converted into millimeters for the analyses. For tongue root measures, the lowest angle at which the tongue root was visible for all tokens of a vowel pair was used. For instance, if 30 degrees was the lowest angle at which the tongue root of all tokens of [u] and [ʊ] were visible, then 30 degrees was used. The differences in the measurement angles across distinct vowels (e.g. between high and mid vowels) for each participant were minimal. For measures of tongue body, height and place specifications of vowels were the main factors in determining the measurement points. The highest point in the midsaggital arc for the purpose of height measurement was determined by assuming a slight tilt of the arc to approximate standing posture. Sample images are shown in Fig. 1.

In the results reported below, participant AIM, the first to be recorded, does not have a harmonic variant of the vowel /i/ due to a mistake in the choice of a target word containing a segment that blocked the spread of harmony. Also, no tongue body measures are available for the three participants recorded in Ottawa due to problems with the recording.

3.3. Results

Table 2 shows results of Student's *t*-tests comparing the individual vowel pairs. In all mean comparisons, a significance level of.05 was used. A shaded cell indicates no significant difference or a difference contrary to the prediction of the relevant hypothesis. Table 3 has a summary of results of 2 × 4 ANOVAs comparing the [−ATR] and [+ATR] values across all vowel pairs.

The results indicate that outside of harmonic contexts, the tongue root position varies systematically across Dagbani vowels for all participants. Class I vowels exhibit a significantly more anterior tongue root position than Class II vowels. For AAB, for instance, the Class I vowels are 5.14 mm more anterior than the Class II vowels. The remaining participants show similar differences. On the tongue body measures, a one-way ANOVA for AIM and IZD shows a significant difference between vowels in the two classes, Table 3. However, a *t*-test of the pairs (Table 2) indicates that [+ATR] vowels are not consistently higher than [−ATR] vowels. For AIM, [i] is the only Class I vowel that has a higher tongue body than its [−ATR] variant. For each of the remaining three pairs [u/ʊ, o/ɔ, e/ɛ], the Class II vowel is higher, contrary to what is predicted if different tongue body positions were the main gesture distinguishing vowels in the two classes.

A comparison of the results of the two measures (Fig. 2) shows a more robust difference in tongue root position. For AIM, Class I vowels are 5.28 mm more anterior than Class II vowels in tongue root position but 1.15 mm higher than Class

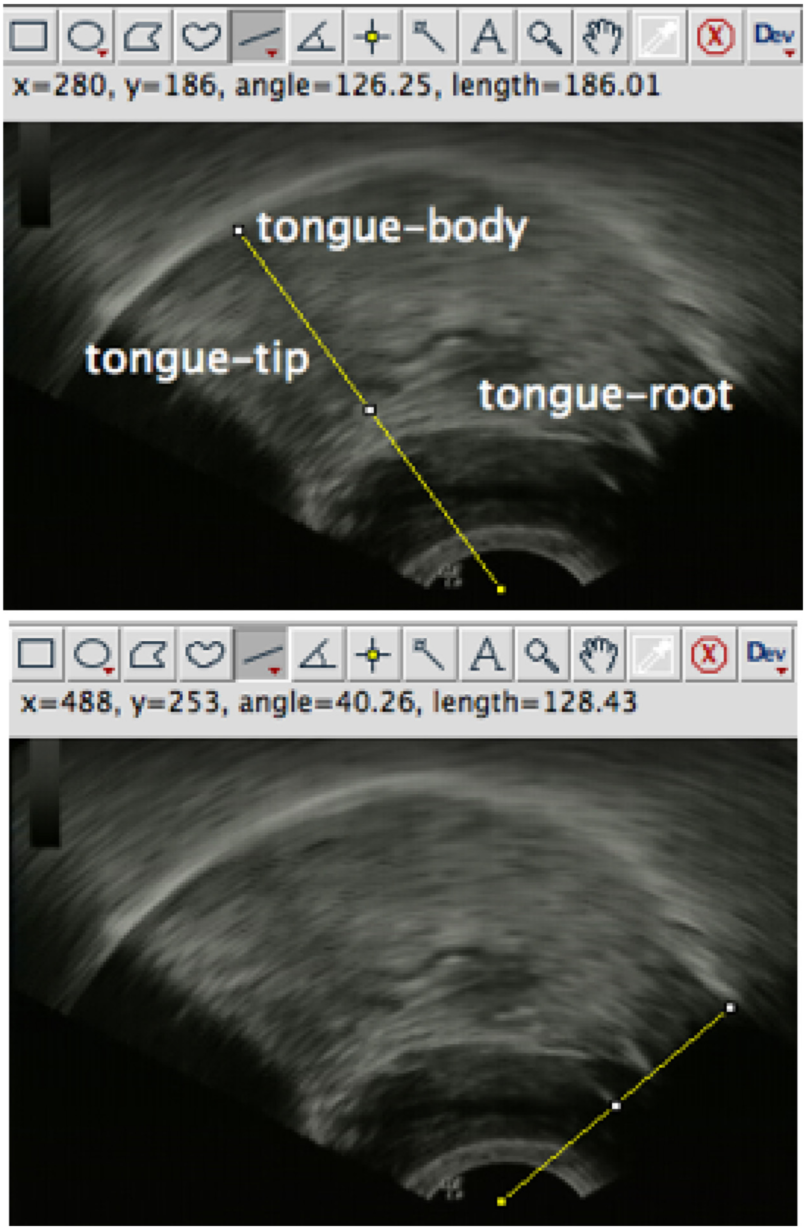

Fig. 1. Sample frames showing measurements of the tongue body(top) and tongue root (bottom) positions in ImageJ for participant AIM. The angle at which both positions were measured are shown in the top part of each frame along with the length of the measurement line.

II vowels in tongue body. For IZD, Class I vowels are 6.07 mm more anterior than Class II vowels in tongue root gesture but 3.72 mm higher than Class II vowels in tongue body.

3.4. Discussion

The results of Experiment 1 are consistent with the Tongue Root Gesture Hypothesis, that vowel pairs within the two classes are indeed distinguished consistently by a tongue root feature. The robust differences in tongue root gesture between Class I and Class II vowels contrasts with the tongue body measures for which (i) there are no significant differences or (ii) observed differences are opposite the direction of the prediction for three of the four pairs for participant AIM, and one pair for IZD. The results support the analysis of these vowels using the feature [ATR].

Table 2
Mean differences (in mm) of tongue root position and tongue body height for all vowel pairs and participants. In all comparisons, the tongue root/tongue body position of the first vowel/vowel class from the transducer is greater than that of the second by the value shown.

Tongue root	Class II–Class I	[ɨ]–[i]	[ʊ]–[u]	[ɛ]–[e]	[ɔ]–[o]
AAB	5.14 $p < .0001$	5.99 $p < .0001$	5.37 $p < .0001$	5.29 $p < .0001$	4.25 $p < .0001$
AB	4.21 $p < .0001$	4.0 $p < .0001$	3.54 $p < .0001$	4.94 $p < .0001$	3.72 $p < .0001$
AIM	5.28 $p < .0001$	5.47 $p < .0001$	2.68 $p < .0001$	3.4 $p < .0001$	7.69 $p < .0001$
HS	3.32 $p < .0001$	5.55 $p < .0001$	1.87 $p < .0001$	1.72 $p = .0003$	3.30 $p < .0001$
IZD	6.07 $p < .0001$	8.32 $p < .0001$	6.83 $p < .0001$	5.35 $p < .0001$	2.82 $p = .0002$

Tongue body	Class I–Class II	[i]–[ɨ]	[u]–[ʊ]	[e]–[ɛ]	[o]–[ɔ]
AIM	1.15 $p = .0073$	5.52 $p < .0001$	−0.07 $p = .8781$	−1.28 $p = .0019$	−1.81 $p = .0002$
IZD	3.72 $p < .0001$	6.42 $p < .0001$	1.4 $p = .262$	5.13 $p < .0001$	0.07 $p = .897$

Table 3
Summary of results of one-way ANOVA for each participant (Experiment 1).

Tongue root	DF	*F*	MSE	*p*-Value
AAB	1, 182	160.15	7.55	$p < 0.0001$
AB	1, 118	178.41	2.97	$p < 0.0001$
HS	1, 121	94.33	3.56	$p < 0.0001$
AIM	1, 137	114.36	8.47	$p < 0.0001$
IZD	1, 141	161.50	8.16	$p < 0.0001$

Tongue body	DF	*F*	MSE	*p*-Value
AIM	1, 137	7.43	6.24	$p = .0073$
IZD	1, 141	55.14	8.97	$p < 0.0001$

4. Experiment 2: Testing the Harmonic [ATR] Hypothesis

4.1. Introduction

This experiment tests whether the tongue root position accounts for the difference between harmonic Class I vowels and Class II vowels.

4.2. Methods

The methods for Experiment 2 were the same as those for Experiment 1, except that Class II vowels were compared with harmonic Class I vowels and thus included measures of the low vowel pair. The stimuli are shown in (8).

(8) Stimuli for Advanced vowels in harmonic domains

	UR (Class II)		**Surface Class I harmony**	
a.	/ɨ/	/bíh-ɨ́/	[bíh-í]	‘child-pl.’
c.	/ɛ/	/dɛ́dɛ́/	[dédé]	‘exact’
d.	/ʊ/	/tí-bʊ́/	[tí-bú]	‘give-ing’
e.	/ɔ/	/dɔ́r-ó/	[dór-ó]	‘disease-sg.’
f.	/a/	/gár-ó/	[gə́r-ó]	‘bed-sg.’ (IZD only)
g.	/a/	/tàdáb-ó/	[tə̀də́b-ó]	‘writing ink-sg.’ (others)

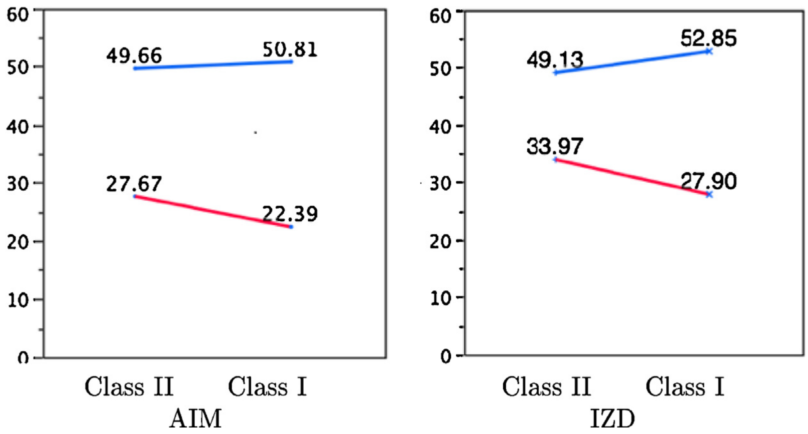

Fig. 2. Mean comparisons of tongue root and tongue body differences for [−ATR] vowels and [+ATR]. The top line represents tongue body measures, the bottom line represents tongue root measures.

Table 4
Mean value differences in tongue root and tongue body (in mm) between [−ATR] vowels and harmonic [+ATR] vowels (Experiment 2).

[tongue root]	Class II - Class I	[ɨ] - [i]	[ʊ] - [u]	[ɛ] - [e]	[ɔ] - [o]	[a] - [ə]
AAB	2.97 *p* < .0001	3.86 *p* < .0001	0.52 *p* = .407	3.74 *p* < .0001	2.49 *p* = .0001	4.57 *p* < .0001
AB	5.30 *p* < .0001	5.02 *p* < .0001	5.48 *p* < .0001	7.57 *p* < .0001	6.09 *p* < .0001	2.73 *p* < .0001
AIM	3.61 *p* < .0001		1.38 *p* = .064	3.40 *p* < .0001	6.35 *p* < .0001	7.88 *p* < .0001
HS	5.56 *p* < .0001	7.87 *p* < .0001	2.48 *p* < .0001	5.50 *p* < .0001	6.38 *p* < .0001	5.33 *p* < .0001
IZD	5.50 *p* < .0001	5.43 *p* < .0001	0.72 *p* = .477	6.17 *p* < .0001	6.24 *p* < .0001	5.98 *p* < .0001

[tongue body]	Class I - Class II	[i] - [ɨ]	[u] - [ʊ]	[e] - [ɛ]	[o] - [ɔ]	[ə] - [a]
AIM	−0.09 *p* = .785		−1.80 *p* = .0013	0.78 *p* = .1193	−2.15 *p* = .0002	2.17 *p* < .0001
IZD	1.15 *p* = .0067	3.82 *p* < .0001	0.81 *p* = .273	2.40 *p* = .0003	0.68 *p* = .304	0.46 *p* = .39

4.3. Results

The mean values of *t*-tests for all participants are shown in Table 4. Table 5 shows results of 2 × 5 ANOVAs comparing the tongue root and tongue body measures across all vowel pairs. The results indicate that within harmonic contexts, the tongue root position varies systematically across Dagbani vowels for all participants. Harmonic Class I vowels exhibit a significantly more anterior tongue root position than Class II vowels. A comparison within each pair indicates that with the exception of [u/ʊ] for AAB, AIM, IZD, each [+ATR] vowel has a significantly more anterior tongue root position than its [−ATR] variant, as Table 4 shows. For tongue body measures, when Class II vowels are compared to Class I vowels, the results show a marginally significant difference for IZD, with Class I vowels only 1.15 mm higher than Class II vowels in tongue body position. Within individual pairs, only the non-back pairs [i/ɨ, e/ɛ], show significant differences.

For AIM, only the low vowels [ə, a] show significant differences in the direction of the prediction. The difference between [e] and [ɛ] is not significant, while the back vowel pairs show differences contrary to the direction of the prediction of the hypothesis that tongue body height characterises the distinction between the vowels. Class I [o, u] show a lower tongue body positions than [ɔ, ʊ]. The effect of these results is a non-significant combined difference between Class I and Class II vowels for this participant. The tongue body results are thus inconsistent: in some pairs Class I vowels are higher, in other pairs Class II vowels are higher and in yet other pairs there are no significant differences.

When tongue root and tongue body results are compared, the mean difference in tongue root position is greater than that between tongue body position. In tongue root position, harmonic [+ATR] vowels are 5.37 mm more anterior than [−ATR] vowels. In tongue body position, they are 1.12 mm higher than [−ATR] vowels, as Fig. 3 shows.

Table 5
Summary of results of one-way ANOVA for each participant (Experiment 2).

Tongue root measures	DF	*F*	MSE	*p*-Value
AAB	1, 241	60.29	8.89	$p < 0.0001$
AB	1, 149	254.05	4.17	$p < 0.0001$
HS	1, 158	258.22	4.78	$p < 0.0001$
AIM	1, 139	37.34	12.32	$p < 0.0001$
IZD	1, 151	110.22	9.81	$p < 0.0001$

Tongue body measures	DF	*F*	MSE	*p*-Value
AIM	NS	NS	NS	NS
IZD	1, 151	75.57	6.24	$p = 0.0067$

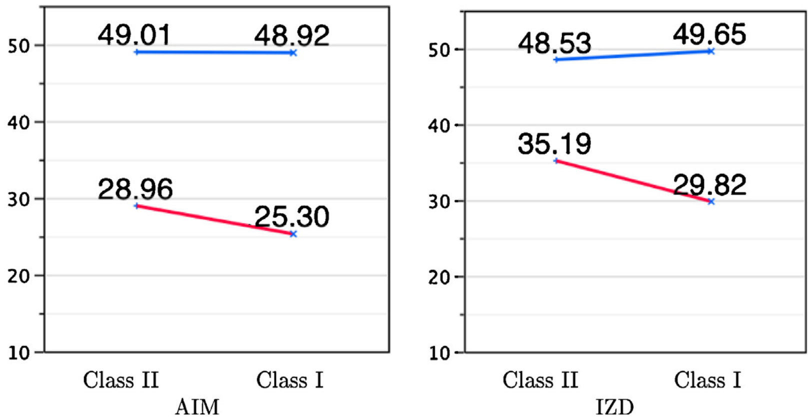

Fig. 3. Mean comparisons of tongue root and tongue body differences for [−ATR] and harmonic [+ATR] vowels for AIM (left) and IZD (right). Top line represents tongue body, bottom line represents tongue root.

4.4. Discussion

The significantly more anterior tongue root position for Class I vowels, relative to Class II vowels shows that a tongue root gesture more consistently defines the difference between vowels in the two classes. The inconsistent and less significant results for tongue body height suggest that the raising of the tongue body is not an independent gesture, even though it may be needed to enhance the difference between vowels in the two classes. The results show further evidence supporting this conclusion. First, two of the participants who lack significant differences in tongue root gesture for the high back vowels also lack differences in tongue body gesture for these vowels in the direction of the prediction. What is crucially needed to argue for an independent tongue body gesture is an instance where a speaker who shows non-significant tongue root differences for vowels in one pair shows significant tongue body differences for vowels in the same pair. However, such results are lacking. Second, while all participants show significant differences in tongue root gesture for all vowel pairs except [ʊ, u], there are no significant differences in tongue body gesture for back vowels in the direction of the prediction that Class I vowels have a higher tongue body than Class II vowels. Given the varying nature of the results, the significant difference in tongue body position found for IZD is likely part of the phonological tongue root gesture. Given the hydrostatic nature of the tongue, a tongue-root advancement gesture may be accompanied by tongue body raising.

While the results of the two preceding experiments support a consistent tongue root gesture distinguishing vowels in the two classes, the results also reveal varying degrees of robustness in the observed differences. For instance, harmonic [u] is not significantly different from [ʊ] for some speakers. Could it be that the change in tongue root gesture observed in harmonic contexts is merely co-articulatory? The next two experiments address this question. Experiment 3 compares harmonic and non-harmonic [+ATR]; Experiment 4 investigates whether the assimilatory effects extend over a longer distance. Results of these two experiments are needed to provide a conceptual basis for investigating the Direct Mapping Hypothesis in Experiment 5. This is because a distinct gesture from neutral position for the dominant value of [ATR] can only be expected if the surfacing of [+ATR] vowels in all contexts is phonological. Harmonic [+ATR] vowels resulting from phonetic interpolation provides a weak basis to expect such a distinct gesture.

Table 6
Mean value differences in tongue root between harmonic and non-harmonic Class I vowels.

	All vowels	[i]	[u]	[e]	[o]
Non-harmonic vowels more advanced					
AAB	2.56 $p < .0001$	2.12 $p = .0037$	4.85 $p < .0001$	1.56 $p = .016$	1.76 $p = .0745$
AIM	0.98 $p = .0354$		−1.30 $p < .0001$	−.005 $p = .992$	1.33 $p = .062$
IZD	1.27 $p = .022$	2.89 $p < .0001$	6.11 $p < .0001$	−0.82 $p = .0586$	−3.43 $p < .0001$
Harmonic vowels more advanced					
AB	1.75 $p < .0001$	1.006 $p = .0217$	1.93 $p = .0004$	2.63 $p = .0002$	2.36 $p < .0001$
HS	2.33 $p < .0001$	2.32 $p < .0001$	0.61 $p = .193$	3.78 $p < .0001$	3.08 $p < .0001$

5. Experiment 3: Harmonic versus non-harmonic [+ATR] vowels

5.1. Introduction

This experiment determines the degree of assimilation in harmonic contexts by comparing the tongue root positions of harmonic and non-harmonic Class I vowels. If the assimilation is phonological, little or no difference is expected between the tongue root positions of harmonic and non-harmonic [+ATR] vowels. If the assimilation is merely co-articulatory, the tongue root position of non-harmonic Class I vowels must be systematically more anterior than that of harmonic Class I vowels.

5.2. Methods

Experiment 3 makes use of figures on the tongue root position of non-harmonic Class I vowels obtained in Experiment 1 and figures on the tongue root position of harmonic Class I vowels obtained in Experiment 2. The two were compared statistically.

5.3. Results

Results of this experiment show some differences between harmonic and non-harmonic [+ATR] vowels. However, these differences do not systematically indicate which of the two Class I vowel sets have a more Advanced Tongue Root than the other. For AAB, AIM, and IZD, the tongue root of non-harmonic [+ATR] vowels is more anterior than that of harmonic [+ATR] vowels. For AIM, this difference does not seem to be really significant. The significance level at $p = .0354$ could be a Type 1 error. AB and HS each has a more Advanced Tongue Root position for harmonic than non-harmonic vowels. The mean values of *t*-test for all participants are shown in Table 6.

5.4. Discussion

Results of Experiment 3 indicate that the phonological contexts in which a [+ATR] vowel is derived does not determine the position of the tongue root. If context were a factor, we would have noticed (1) a systematic variation in tongue root position for all vowel pairs, and (2) the same variation for all participants. The results support the conclusion that the assimilation in harmonic contexts is not co-articulatory. The constraints that derive the assimilatory pattern are not less phonological than those that derive [+ATR] vowels in non-harmonic contexts.

6. Experiment 4: Distance effects

6.1. Introduction

This experiment examines whether harmony takes place when the target vowel is more than one syllable away from the trigger, and whether the degree of assimilation diminishes when the target is farther from the trigger. Because the presence of any diminishing effects in advancement over a longer distance could be an indication of a non-phonological pattern of assimilation, the lack of such effects strengthens the conclusion that the assimilation is phonological.

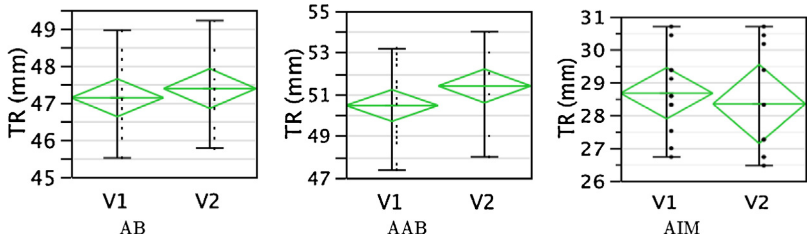

Fig. 4. Variability charts of tongue root distance from transducer for V1 and V2.

6.2. Methods

The target vowel was [a] in */tàdáb-ô/* ‘writing ink’. The tongue root position of [a] in *ta* (V2), was compared to that of [a] in *da* (V1). The results are for 3 participants only. Tongue root images for the two target vowels for HS and IZD were not visible at the same angle or insufficient for statistical comparison.

6.3. Results

Results of this experiment show no significant difference in the tongue root gestures of the two target vowels. Variability charts are shown in Fig. 4.

6.4. Discussion

The results in Experiment 4 support the prediction that distance from the trigger does not significantly reduce the level of assimilation of a target vowel. They support the view that the emergence of [+ATR] in harmonic contexts is phonological, not co-articulatory.

The results are significant in other respects, given that [a] was the target vowel. First, in Dagbani phonology, [a] does not assimilate completely to a [+ATR] vowel trigger in harmonic domains. Affix [ɨ] neutralises with [i] trigger, while [ɛ, ɔ] impressionistically neutralise with final [e, o] triggers respectively. While being neutralising is not the basis for an assimilatory pattern to be phonological, it does make a stronger case for being phonological harmony. The categorical nature of the assimilatory effect observed in this experiment argues against any potential doubts as to the phonological status of surface [a] in harmonic contexts.

Second, /a/ is the only vowel that is most often claimed to lack an advanced variant in many languages with [ATR] harmony, with some harmony theories (e.g. Goad, 1993) claiming that the [+low] and [+ATR] feature specifications are incompatible. The results show that the low vowel bears the same phonological tongue root feature specification that distinguishes Class I and Class II vowels.

7. Experiment 5: Testing the Direct Mapping Hypothesis

7.1. Introduction

This experiment tests the Direct Mapping Hypothesis and its prediction that the active [+ATR] feature specification for a language Type A is directly correlated with a tongue root position anterior to the neutral rest position.

7.2. Methods

For this experiment, the tongue root positions of Class I and Class II vowels were compared with the tongue root rest position, the inter-speech posture.

7.3. Results

The results of Experiment 5, displayed in Table 7, show that for all the participants, Class I vowels have a significantly and systematically anterior tongue root position compared to the ISP. Class II vowels for 4 of the participants were also significantly anterior to the ISP. However, for participant AAB, the tongue root position of Class II vowels was significantly

Table 7
Mean differences of tongue root positions between vowels in each class and the ISP. In the second and third columns, the mean default tongue root position is greater than the mean tongue root position of Class I or Class II vowels by the value shown. In the fourth column, the advancement of Class I vowels from the ISP is greater than the advancement of Class II vowels from the ISP by the value shown.

	ISP–Class I	ISP–Class II	Class II–Class I
AAB	2.10 ($p = .0088$)	−1.79 ($p = .0057$)	3.89
AB	6.62 ($p < .0001$)	2.1 ($p < .0001$)	4.52
AIM	7.75 ($p < .0001$)	3.36 ($p < .0001$)	4.39
HS	6.89 ($p < .0001$)	2.11 ($p < .0001$)	4.78
IZD	11.24 ($p < .0001$)	5.18 ($p < .0001$)	6.06

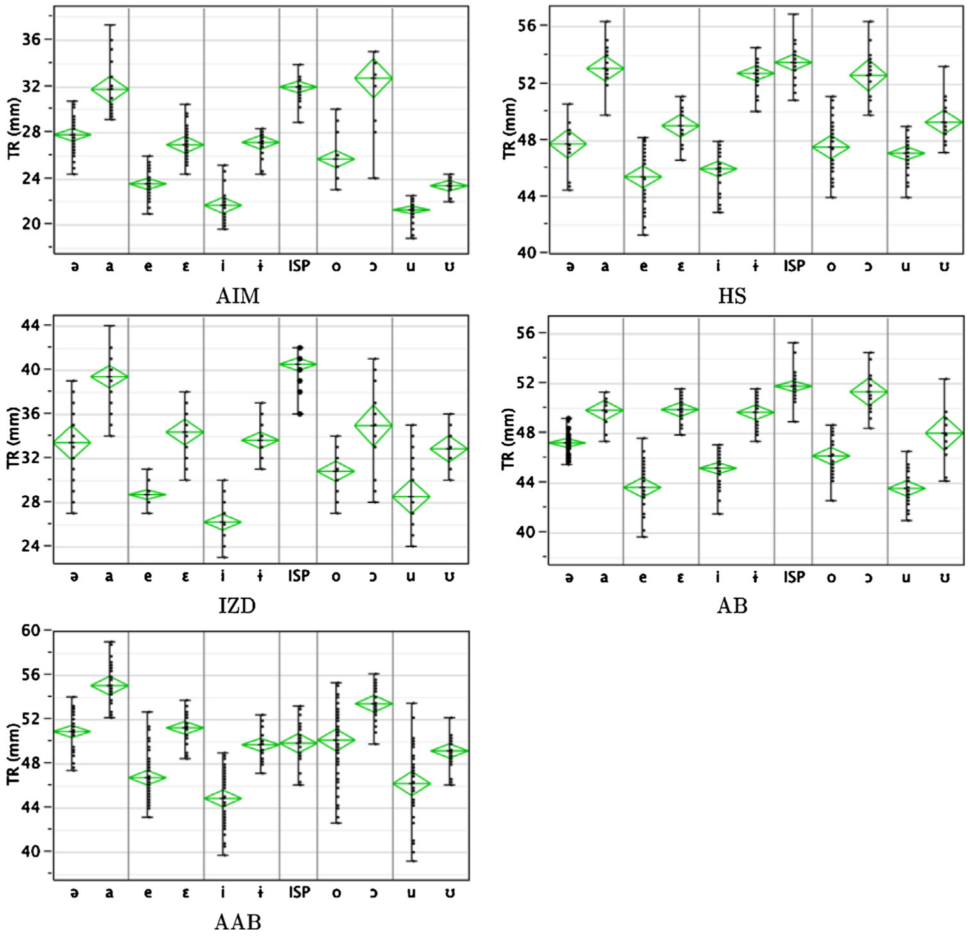

Fig. 5. Variability charts of tongue root distance from transducer for all vowels and the ISP.

posterior to the ISP. The Student's *t*-tests of individual vowels in Fig. 5 show a greater variability. While no [+ATR] vowel is significantly posterior to the ISP, within some of the participants, some [−ATR] vowels are not anterior to the neutral position.

7.4. Discussion

Unlike the Class I vowels, which display consistent advancement from the ISP, variations in the positions of individual Class II vowels relative to the ISP across all participants give an indication that Class II vowels do not have a unique displacement from the neutral position. The observed differences in tongue root gestures for vowels in the two classes are consistent with the hypothesis that the dominant [+ATR] value of Dagbani maps directly onto an anterior gesture of the tongue root while the recessive [−ATR] value has a more variable tongue root position. Vowels that lack [+ATR] specification also largely lack a unique tongue root gesture. Measured from the neutral position, the tongue root may be anterior, posterior or lack any displacement.

8. Summary and conclusions

The experiments in this paper were set out to answer basic empirical questions on the articulatory basis for tongue root features as they manifest in languages with tongue root harmony. In addition to replicating the findings of previous articulatory studies to the effect that [+ATR] vowels have a more anterior tongue root than [−ATR] vowels, results of the first two experiments also rule out the tongue body gesture as a consistent alternative gesture distinguishing [+ATR] vowels from [−ATR] ones. For Dagbani, the results also confirm that (1) Class I vowels that surface in harmonic contexts have the same degree of tongue root advancement as those that surface in non-harmonic contexts, (2) the harmonic pattern affects vowels of all heights, including the low vowel, and (3) tongue root harmony in Dagbani takes place regardless of the relative distance between the trigger and target. Taken together, the results of these studies provide support for the assimilatory processes that produces [+ATR] vowels being a case of phonological harmony.

Results of Experiment 5 testing the Direct Mapping Hypothesis support a direct mapping between the articulatory position of the tongue root and the position of [+ATR] vowels in a language with dominant [+ATR] feature. The results imply that tongue root position indeed plays a distinct role in defining phonological tongue root features. The results of all the experiments are significant in light of previous assumptions on the nature of tongue root features in general as well as assumptions on tongue root harmony in Dagbani. For instance, previous proposals that question or reject the possibility of low vowels bearing phonological [ATR] indirectly reject the presence of an unhindered cross-height [ATR] harmony.

The conclusions of Experiment 5 obviously need to be supported by studies of different tongue root harmony patterns. However, regardless of what the results of such future studies may be, the broader conclusion in previous studies that is replicated in this study is that, contrary to previous claims such as Hyman (1988) and Salting (1998), tongue root articulatory gestures may not be ignored in any accurate definition of tongue root features.

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