Three-dimensional ultrasound images of Polish high front vowels

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Three-dimensional ultrasound images of Polish high front vowels

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The 3-D ultrasound method has been applied to collect data on Polish high front vowels. In particular, Polish has one unambiguous high front vowel and another one that in the phonological literature is variously referred to as high central or back unrounded and transcribed as [ɨ]. While there exists a sizeable body of articulatory research on Polish, including X-rays from as early as the 50s and 60s, the ultrasound data reveal more detail about the position of the tongue center and tongue root. The data evaluated so far support the view that the vowel transcribed as [ɨ] is a front vowel. The two front vowels differ in the position of the tongue root, relative raising of the tongue, and extent of lip gesture, but do not differ substantially with regard to tongue body advancement on the font-back axis. The data also capture the temporal aspect of speech, and together with time-aligned audio recordings and video recordings of the lips, allow for fine-grained analysis of the acoustic effects of these articulatory gestures.

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1. INTRODUCTION

The vowel system of Polish contains six basic vowel phonemes, as illustrated in Table 1. There is one unambiguous "high front" vowel, /i/. The vowel transcribed as /ɨ/ has been variously described as "high central" or "back unrounded" in the phonological literature (Rocławski 1976, Rubach 1984, Gussmann 2007, Rydzewski 2016), and as "high front" in the phonetics literature (Wierzchowska 1967, Dukiewicz 1995). In Table 1 it is tentatively placed as a "high front" vowel.

Table 1. Traditional Polish vowel phoneme inventory.

Polish vowel phonemes	
i, ɨ	u
e	o
a	

Tied together with the question of where /ɨ/ belongs along the front-central-back axis are the additional issues of 1) vowel allophony and 2) tongue root configuration in Polish vowels. Each of the 4 non-high-front vowel phonemes /e, a, o, u/ has two allophones. One set of allophones occurs only following a prepalatal consonant, while the other set of allophones occurs in non-prepalatal (i.e. "neutral") contexts. In native Polish words, the vowel phonemes /i/ and /ɨ/ are distributed – when following consonants – in the same way as the prepalatal-neutral allophones of the other vowels, with [i] occurring after prepalatal consonants, and [ɨ] occurring in neutral contexts. Unlike the other prepalatal-context vowels, the vowel /i/ can follow an underlying non-prepalatal consonant, but then it causes an underlying neutral consonant to become palatalized. Furthermore, unlike the other neutral vowels, the vowel /ɨ/ and the neutral allophone of /e/ generally cannot co-occur with neutral velar consonants in native vocabulary (although it is possible in twentieth century loan words).

The nature of /ɨ/ in Polish, and its relation to /i/, is therefore complex and remains unresolved. Any solution must include a treatment of the phonetics and phonology of prepalatal consonants, or palatalization more broadly. Cavar (2004) posited a solution in which the vowel /ɨ/ is "high front" like /i/, and in which the prepalatal/neutral dichotomy is defined by advancement/retraction of the tongue root. According to her thesis, this dichotomy is also the source of the distinction between prepalatal consonants and non-prepalatal consonants, as well as the existing phonotactic constraints on the co-occurrence of consonant-vowel sequences. Specifically, prepalatals are the only consonants in Polish with a distinctive, underlying specification for tongue root advancement, and must be followed by a vowel with a compatible tongue root configuration. Additionally, sequences with velar consonants are restricted even further. Front vowels – including /ɨ/ – cannot co-occur with neutral velar consonants in native vocabulary. This is because the velar place of articulation (called "dorsal") is not in agreement with the"front" tongue body position of /i/, /ɨ/ and /e/ (also called "coronal"). This contrasts with the allophones of /u, o, a/, which are "back" ("dorsal") in agreement with the velar stops.

The proposal of Cavar (2004) can be summarized as follows: Both phonotactic and allophonic

patterns suggest that /ɨ/ is a high front vowel, paired with /i/ in the same way as the allophonic prepalatal/neutral vowel pairs. Moreover, the /i/ and /ɨ/ differ from each other in tongue root advancement/retraction, with /i/ specified as [+ATR] and /ɨ/ specified as [-ATR]. Phonetically, therefore, the vowel /ɨ/ is hypothesized to be articulated with a fronted tongue body (in contrast to the neutral allophone of /u/) but a retracted tongue root (in contrast to /i/ and the prepalatal allophone of /u/).

The restriction on /k+ɨ/ sequences does not seem to hold in twentieth century borrowings. Cavar (2007) hypothesized that the tongue body in underlying /ɨ/ following a velar stop is somehow retracted toward the back vowel space, but no experimental evidence was available to support this claim.

While there exists a sizeable body of articulatory research on Polish, including X-rays from as early as the 1950's and 1960's (Koneczna & Zawadowski 1951, Wierzchowska 1967), new ultrasound data reveal more detail about the position of the tongue body and tongue root. Furthermore, prior articulatory descriptions of Polish vowels have not investigated /ɨ/ in different consonantal contexts. The purpose of the present study is to test the hypotheses mentioned above, namely, that /ɨ/ is articulated with a fronted tongue body and a retracted tongue root. Furthermore, the study documents the existence of contextual allophonic variation in the production of /ɨ/ depending on the place of articulation of the preceding consonant.

2. METHOD

Five Polish native speakers (three women, two men) participated in the experiment, which was carried out over 1 to 3 sessions. Participants read word lists consisting of two-syllable nonce words with the shape $C_iV_jC_iV_jC_i$. The consonantal contexts were always one from the set /p, t, k, tɕ/. The vowels included /i, ɨ, u, e, o, a/, and the resulting words followed the phonotactic constraints of Polish, e.g. excluding sequences *tɕɨ (cf. e.g. Cavar 2004:201).

Ultrasound images were recorded with a Philips EpiQ7G system using an xMatrix x6-1 digital 3D transducer secured under the chin using an Articulate Instruments ultrasound stabilization headset. Fully uncompressed DICOM ultrasound files were transferred to a Windows 7 computer for analysis.

Palate impressions were made using dental alginate (Ladefoged 2003), and digitized with a NextEngine 3D laser scanner. The digitized palate impressions were saved in binary STL format. Ultrasound and palate files were analyzed using a custom MATLAB toolbox, called "WASL". Palates were manually registered with the tongue data.

As we collected the ultrasound data, audio was synchronously recorded with a SHURE KSM32 microphone placed approximately 1 meter in front of the participant, at 48kHz sampling rate. At the same time, video was recorded of the speaker from the profile in an attempt to track the lip position.

3. RESULTS

Data from all five participants were analyzed and all five speakers show the same set of articulatory strategies. The following sections present images based primarily on the data from Speaker 5, which illustrate these strategies most clearly. Each tongue shape presented (e.g. in Figures 1 and 3) is from an individual representative token, not an average across multiple tokens.

A. /i/ AND / ɨ/ ARE BOTH FRONT VOWELS

The analysis of the ultrasound images indicate that /ɨ/ is not a back vowel. Figure 1 illustrates this by a comparing of the tongue position in the articulation of /ɨ/ in different contexts (green, red, light blue) with the tongue position in the articulation of the vowel /u/ (dark blue), which is indisputably a back vowel. The highest part of the tongue body for all three instances of (neutral) [ɨ] extends as far forward as approximately 5 cm (measured as the horizontal distance from the anterior edge of the ultrasound image), while the highest part of the tongue body extends only to approximately 7.5 cm for the (neutral) [u].

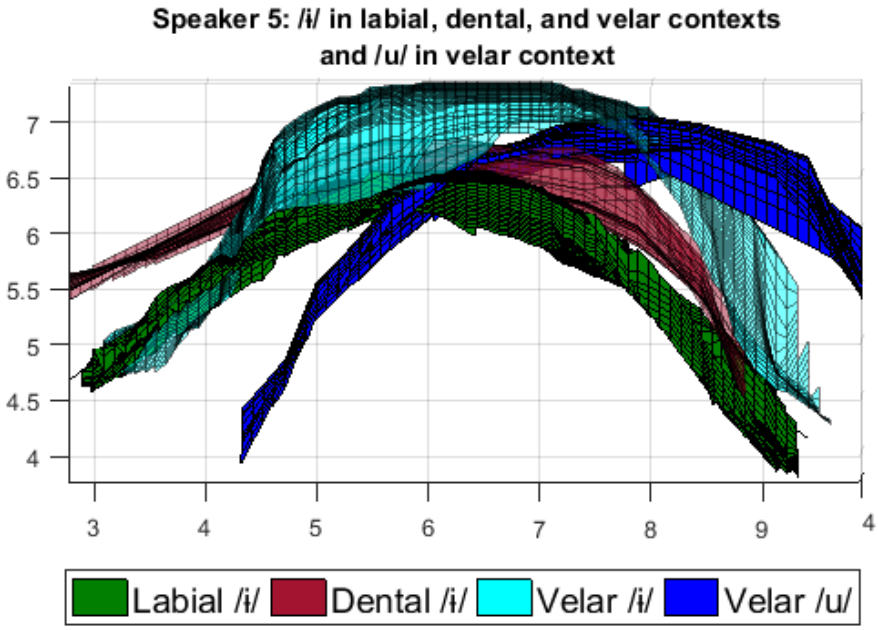

Figure 1. /ɨ/ as a front vowel. Tongue tip (anterior) is to the left.

Figure 2 shows the position of each Polish vowel (neutral as well as prepalatal) in the articulatory space defined by Ladefoged and Maddieson (1996) [p. 284, Figure 9.2]. The x-axis indicates the horizontal distance from the anterior edge of the ultrasound image to the highest point of the tongue, and the y-axis indicates the vertical distance from the bottom edge of the ultrasound image to the same point (i.e. the highest point of the tongue). This figure demonstrates that [ɨ] is positioned similar to the other front vowels [i], [e], and [ɛ], and should therefore be considered a front vowel itself.

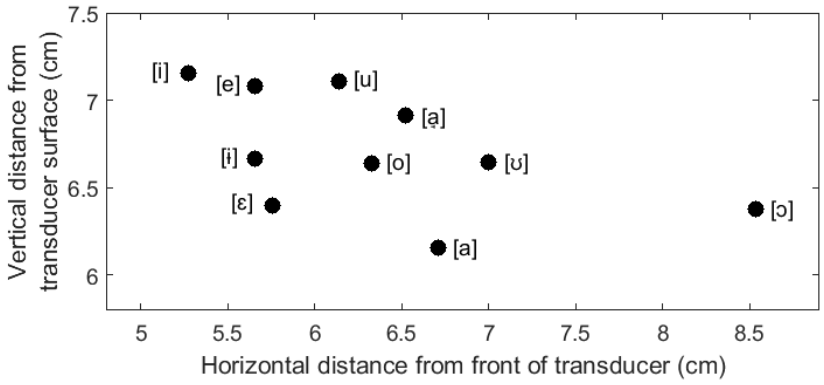

Figure 2. Position of the highest point of the tongue for all Polish vowels, showing that the vowel [i] is a front vowel like [i], [e], and [ɛ].

Figure 3 provides an additional perspective on the position of /ɨ/ on the front-back axis. The point of maximal tongue raising for /i/ and /ɨ/ (traces in black in Figure 3) in dental context differs by approximately 0.5 cm along the front-back axis. For one of the speakers in our study (Speaker 3), the point of maximal constriction was actually further back for /i/ than for /ɨ/. For Speaker 5, the maximal constriction area for both vowels can be roughly located within the 5 cm to 5.5 cm region. In contrast, the maximal constriction for the prepalatal and neutral variants of /u/ are located within the 6 cm to 8 cm region. We conclude that both /i/ and /ɨ/ vowels are articulated with a front tongue position, confirming earlier findings from e.g. Wierzchowska 1967.

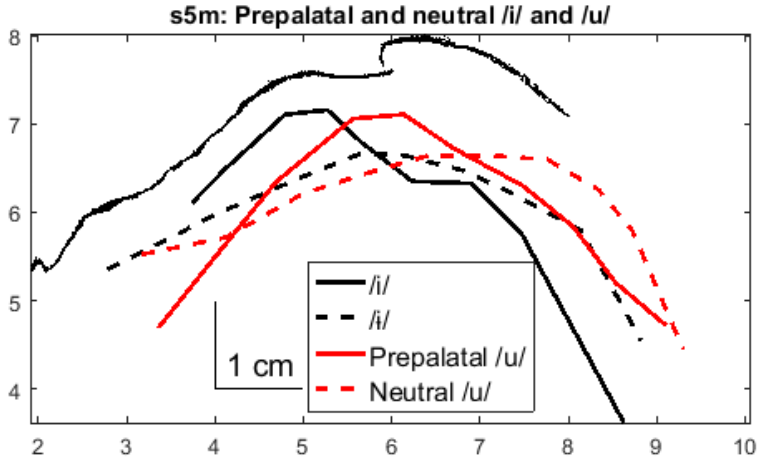

Figure 3. /i/ and /ɨ/ as front vowels. The black line along the top indicates the palate (anterior is to the left). The black lines under the palate are tongue shapes for /i/ and /ɨ/, and red lines are tongue shapes for the /u/ vowel in prepalatal and neutral contexts.

B. /i/ ACROSS DIFFERENT CONSONANTAL CONTEXTS

Figure 4 shows the tongue shapes for /i/ in labial and dental contexts. With the exception of slight tongue blade elevation in the dental context, differences in the articulation of /i/ in these two context are minimal.

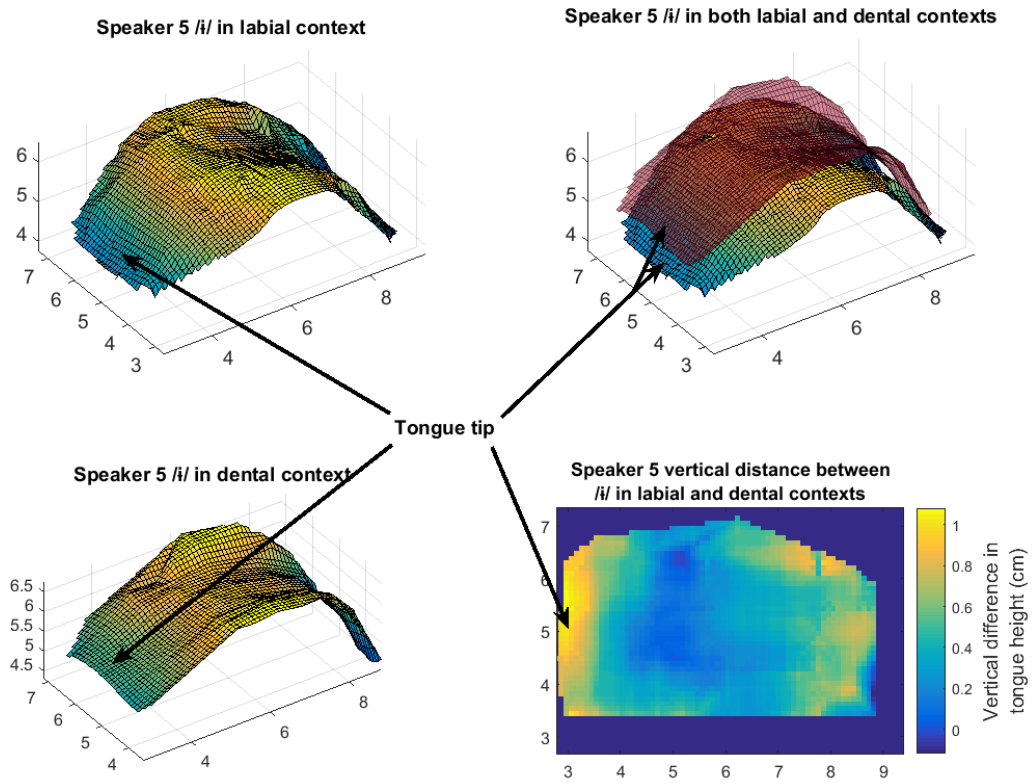

Figure 4. /i/ after a labial /p/ and dental /t/. Tongue tip is to the left.

Figure 5 shows the tongue shape of /i/ in velar context. In comparison with the tongue shape in labial and dental contexts (cf. Figure 4), the region of maximal constriction is substantially longer in the velar context. (Figure 1 also shows this distinction.) The region of maximal constriction extends from the region typical for /i/ in labial and coronal context (approximately 5.5 cm) and then further back to near the region typical for the neutral back vowel /u/ (approximately 7 cm).

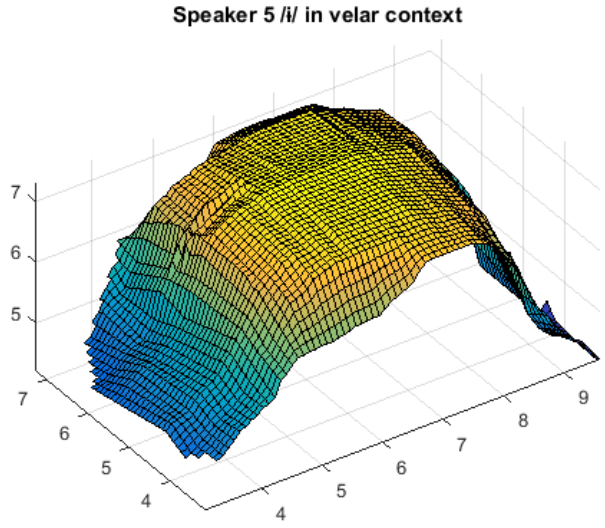

Figure 5. /i/ after a velar /k/. Tongue tip is to the left. The region of maximal constriction is long, extending from approximately 5.5 cm to 7 cm.

C. TONGUE ROOT POSITION

The collected 3-D ultrasound data allows us a glimpse at the position of the tongue root. For all speakers in the study we have observed a contrast in the position of the tongue root for the pair /i/-/ɨ/. For /i/, there is a conspicuous grooving in the back of the tongue and/or clear advancement of the whole tongue base. This is very well visible in Fig. 6, where the groove goes all the way from the tongue dorsum into the tongue base.

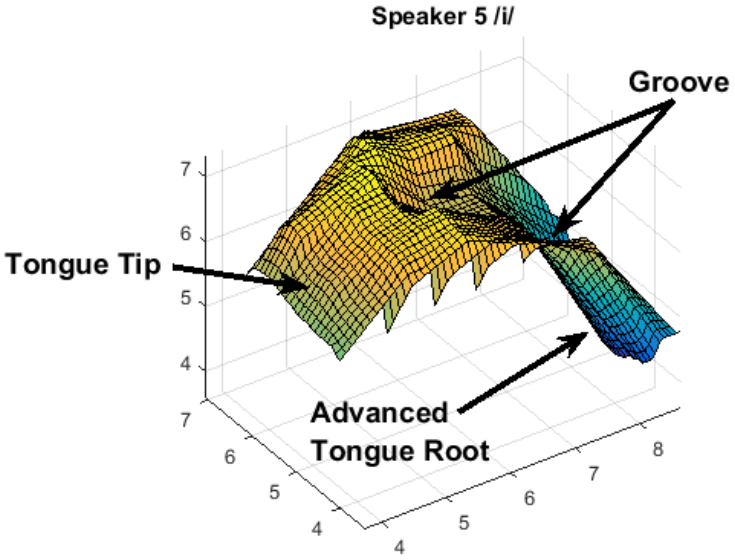

Figure 6. /i/ in the prepalatal consonant context. Tongue tip is to the left.

This fronting of the whole tongue root was found to be typical for all vocalic allophones in the prepalatal consonant context (cf. Cavar et al, 2017), e.g. /u/ following /tɕ/, shown in Figure 7. Furthermore, while the prepalatal vocalic allophones do occasionally differ from their neutral context counterparts in terms of a combination of some fronting and/or raising, the property that is present for all speakers and realizations is the advancement of the tongue root and a relative expansion of the pharyngeal cavity in the prepalatal allophones.

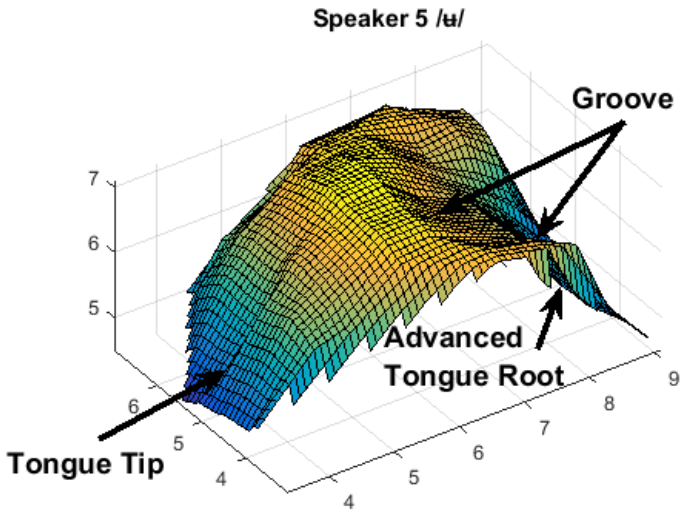

Figure 7. /u/ in the prepalatal consonant context. Tongue tip is to the left.

No such advancement of the tongue root can be observed in the articulation of /ɨ/, although a broad groove in the region of the tongue dorsum may be created through raising the lateral edges of the tongue, as shown in Figure 8.

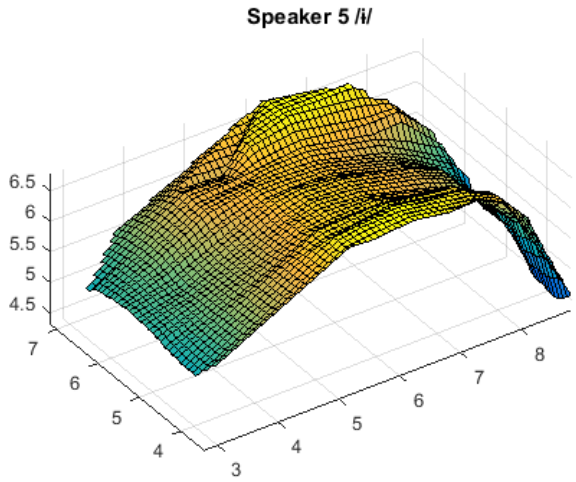

Figure 8. /ɨ/ in the dental context. Tongue tip is to the left.

This configuration of the tongue root is typical for other neutral (that is non-prepalatal) context vowels, cf. neutral context /u/ in Fig. 9.

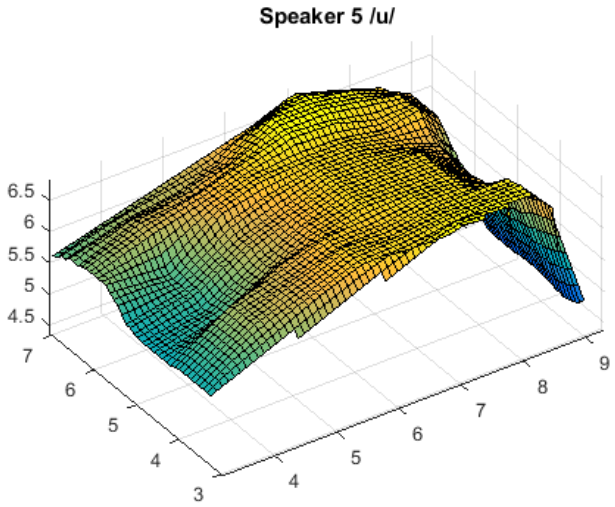

Figure 9. /u/ in the neutral (dental) consonant context. Tongue tip is to the left.

D. LIP POSITION

Figure 10 illustrates lip gestures observable from video recordings made during the experiment. The vowel /u/ is articulated with significant rounding of the lips, irrespective of whether in the neutral consonant or prepalatal consonant context. However, based on the data evaluated so far, no conclusive generalization could be established with regards to the role of lip position in the articulation of /i/ versus /ɨ/, except for the lack of rounding in both.

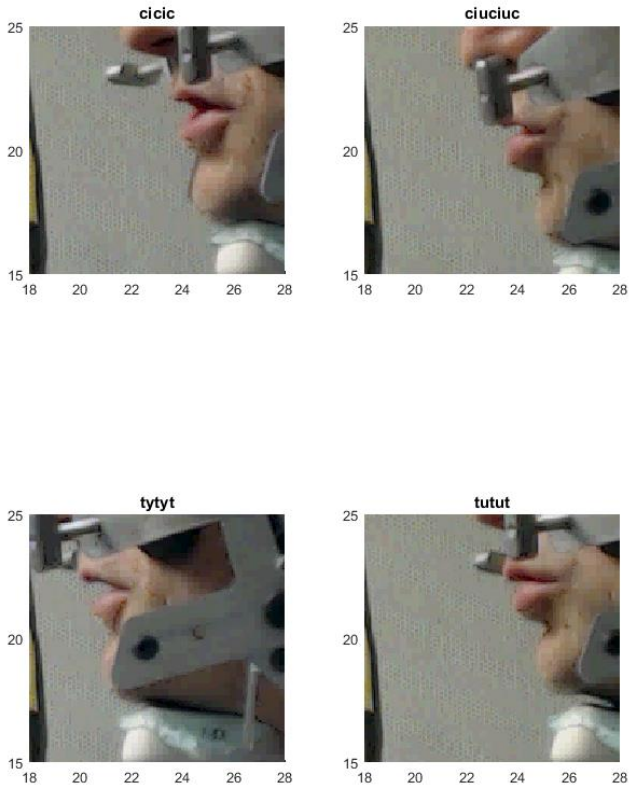

Figure 10. Lip position in the articulation of high vowels in Polish. Speaker 5. Top left corner: /i/ between prepalatals. Top right corner: /u/ between prepalatals. Bottom left corner: /ɨ/ between neutral dentals. Bottom right corner: /u/ between neutral dentals.

E. COMPARISON: /i/ AND /ɨ/ IN THE VELAR CONSONANT CONTEXT

While we have observed allophony for /ɨ/ in the velar consonant context, no variation in the articulation of /i/ across different consonantal contexts could be detected. In the case of /i/, it is rather the consonant that bears the burden of assimilation to the vowel, which yields a 'palatalized' consonant. For instance, a velar followed by /i/ becomes pre-velar (perhaps palatal). The vowel /i/ in prepalatal and (pre)velar contexts is shown in Figure 11, and are virtually identical. A separate perspective on the /i/ in (pre)velar context is shown in Figure 12.

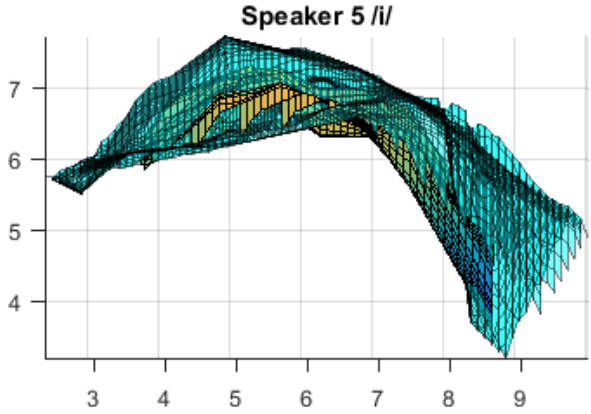

Figure 11. /i/ in the (pre)velar and prepalatal context. Tongue tip is to the left. The two tongue shapes are very similar.

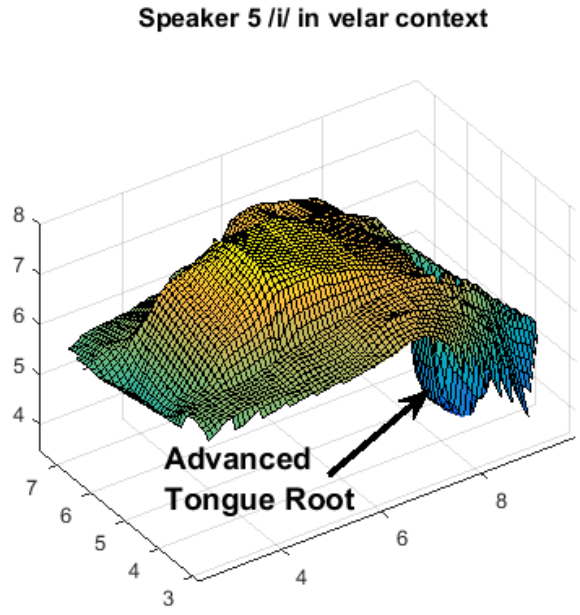

Figure 12. /i/ when following a 'palatalized' velar. Tongue tip is to the left.

On the other hand, /ɨ/ in the velar consonant context is articulated with a conspicuously long constriction that additionally incorporates part of the back of the tongue, as shown in Figure 13.

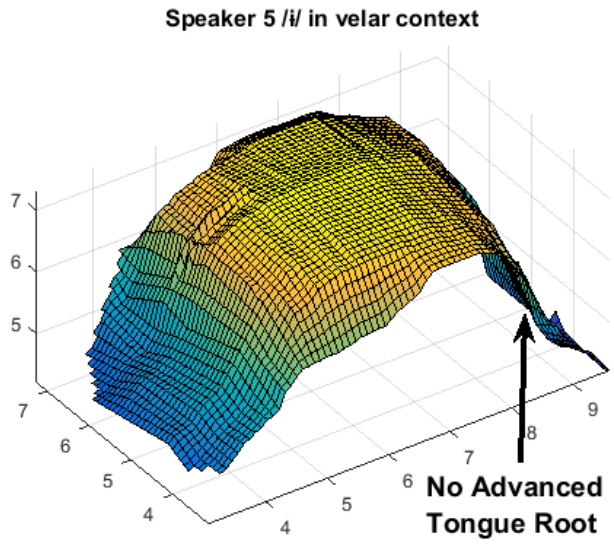

Figure13. /i/ in velar context. Tongue tip is to the left.

Apart from the position of the back of the tongue, /i/ and /ɨ/ differ in the position of the tongue root with an evident tongue root advancement for /i/.

F. COMPARISON: /ɨ/ IN THE VELAR CONSONANT CONTEXT VERSUS /u/ IN THE PREPALATAL CONSONANT CONTEXT

The role of the tongue root is further evident if we compare /ɨ/ with an allophonic variant of /u/ as articulated between prepalatals. Figure 14 provides such a comparison. In this context /u/ is substantially fronted, though the point of the maximal constriction is still posterior to the "beginning" of the constriction for /ɨ/ (cf. Figure 2). Moreover, the two vowels differ in that for prepalatal /u/, the tongue root is substantially advanced and there is a prominent groove running from the back of the tongue down to the tongue base, while there is no such groove or tongue root advancement for /ɨ/.

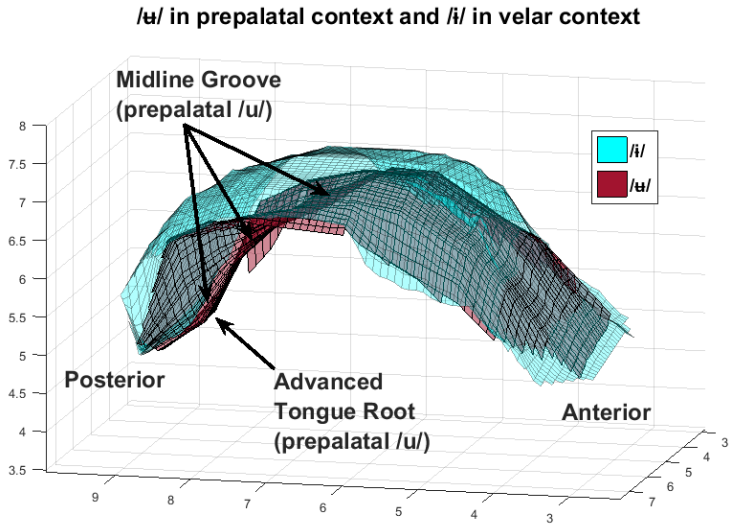

***Figure 14. Prepalatal-context /u/ (red) versus velar-context /i/ (blue). Unlike in Figures 1-13, the tongue tip is to the* right.**

G. TONGUE BODY POSITION ON THE FRONT-BACK AXIS: CORONAL CONSONANT CONTEXT

Figure 3 showed that for both the /i/-/ɨ/ pair and the /u/ in prepalatal vs. neutral contexts, the articulatory contrast within each pair consisted of a raised/fronted tongue body and an advanced tongue root in /i/ and prepalatal /u/, and a lowered/backed tongue body and a retracted (or non-advanced) tongue root in /ɨ/ and neutral /u/. The pattern for both pairs is in fact identical, and the articulatory equivalence of the contrast in both pairs is made evident in Figure 15, in which the two /u/ tongue contours were artificially shifted in the anterior direction to overlap with the /i/-/ɨ/ pair.

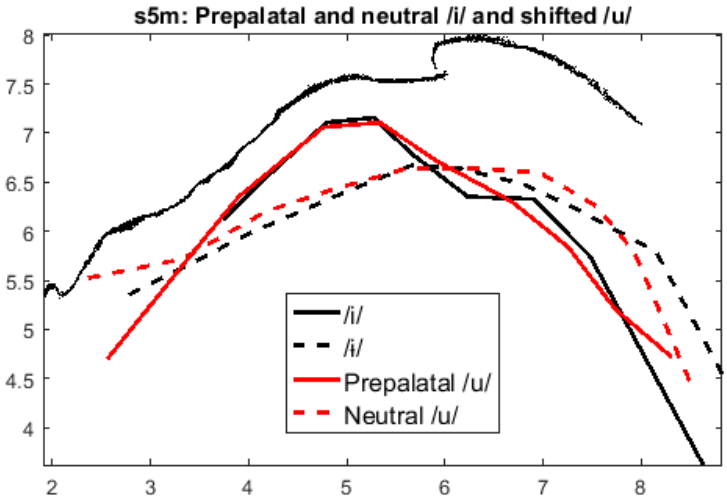

Figure 2. /i/ and /ɨ/ as front vowels. The black line along the top indicates the palate (anterior is to the left). The black lines under the palate are tongue shapes for /i/ and /ɨ/, and red lines are tongue shapes for the /u/ vowel in prepalatal and neutral contexts after being artificially shifted to the left.

4. DISCUSSION

The analysis of the collected ultrasound data for the Polish high vowels leads us to confirm that both /i/ and /ɨ/ in Polish are front vowels. Among all of the front vowels of Polish, there is little difference in the position of the tongue body on the front-back axis, while /i/ is articulated with more raising of the tongue. This raising of the tongue appears to result from a number of different articulatory strategies, most commonly the activation of posterior genioglossus. The consistent observation across speakers is the advancement of the tongue root and a deep groove running along the center of the tongue from the back of the tongue body down to the tongue root for /i/, and the lack of these for /ɨ/. The same basic patterns are observed in the other prepalatal/neutral vowel pairs, further suggesting that /i/ and /ɨ/ form a pair of high front vowels differing only in terms of tongue root advancement. We found no evidence that /ɨ/ is a central vowel with intermediate tongue placement along the front-back axis or with phonological behavior distinguishing it from the front vowels.

We found variation in the articulation of /ɨ/ across contexts. In particular, in the context of a labial or dental stop /ɨ/ is articulated with the maximal constriction located in the same area as /i/ but in the context of a velar stop the constriction is much longer and extends further back from the region typical for /ɨ/ in the labial and coronal contexts.

The findings of this study support an earlier phonological analysis by Cavar (2004), who postulated that /i/ and /ɨ/ are front ("Coronal" in the terminology of Clements and Hume 1995) and the distinction between /i/ and /ɨ/ should be expressed in terms of the phonological feature [ATR] (Advanced Tongue Root) rather than [back], yielding phonological feature specifications for high vowels in Polish as in Table 2.

Table 2. Phonological features for high vowels in Polish (cf. Cavar 2004).

	/i/	/ɨ/	/u/
Major place	Coronal (front)	Coronal (front)	Dorsal (back)
Tongue root position	+ATR	-ATR	underspecified

Cavar (2004:203) also discusses phonotactic constraints pertaining to, among others, velar consonant + vowel sequences in Polish. Sequences /*ki/ are not attested, and instead the consonant is allophonically fronted to pre-velar or palatal place, resulting in [ci]. Sequences of velars followed by /ɨ/ are not attested in the native vocabulary but allowed in a handful of newer borrowings. The constraints are summarized in Table 3.

Table 3. Phonotactic constraints on velar + front vowel sequences in Polish (Cavar 2004).

*ki	✔ ci
*kɨ (native vocabulary) versus *cɨ	✔kɨ (new borrowings)

These phonotactic constraints are accounted for by Optimality Theory agreement constraints between the consonant and the vowel, and this in terms of the major place of constriction (Labial, Coronal or Dorsal as used in the feature geometric framework, e.g. in Clements and Hume 1995) but also in terms of ATR (Cavar 2004):

Place Agreement: In a sequence of a velar consonant + vowel, the consonant and the vowel have to share a major place feature specification.

ATR Agreement: In a sequence of a velar consonant + vowel, the consonant and the vowel have to share the tongue root feature.

Place Agreement constraints account for the lack of /kɨ/ in the native vocabulary, as in Table 4. Sequence /ki/ is excluded because velar (Dorsal) /k/ is also articulated without tongue root advancement and specified as [-ATR], so ATR Agreement is violated. For sequence /cɨ/, the consonant and the vowel share feature Coronal but disagree in terms of the tongue root position (pre-velar or palatal consonant is stipulated to be articulated with the advancement of the tongue root, which is not the case for /ɨ/).

Table 4. Agreement constraints at work: native vocabulary (Cavar, 2004)

Native vocabulary	/i/ Coronal +ATR	/ɨ/ Coronal -ATR
[k] Dorsal -ATR	*ki	*kɨ
[c] Dorsal-Coronal +ATR	✔ci	*cɨ

However, the assumption that /ɨ/ is plainly Coronal (front) is problematic if we take into account newer borrowings, which allow a /kɨ/ sequence. For /kɨ/ in the borrowings, Cavar (2007) stipulates that /ɨ/ is in these sequences both Coronal and Dorsal, thus satisfying the Place Agreement Constraint, as shown in Table 5. Under this analysis, both elements of the sequence /kɨ/ are Dorsal. The current study confirms this assumption, demonstrating that /ɨ/ - only in the velar stop context – is both front (Coronal) and back (Dorsal), as evidenced by the long constriction extending into the dorsal region.

Table 5. Agreement constraints at work: new borrowings.

New borrowings	/i/ Coronal +ATR	/ɨ/ Coronal-Dorsal -ATR
[k] Dorsal -ATR	*ki	✔kɨ
[c] Dorsal-Coronal +ATR	✔ci	*cɨ

5. CONCLUSIONS

The ultrasound recordings collected in the current study demonstrate that the two front vowels /i/ and /ɨ/ differ consistently and primarily in the position of the tongue root (and presumably the volume of the pharynx), and secondarily in the degree of the raising of the tongue body. The instances of /ɨ/ do not differ significantly with regards to the tongue body advancement on the font-back axis in the labial and dental stop contexts. In these contexts [ɨ] is an unambiguously front vowel.

An allophonic variation across contexts – depending on the place of articulation of the preceding consonant – has been observed for /ɨ/. The constriction in [ɨ] in the context of the velar

stop – as attested in some newer borrowings – is longer, including the back part of the tongue, supporting Cavar's (2004) analysis that /ɨ/ in this context is both Coronal and Dorsal.

The study raised further questions. Given different phonotactic constraints for sequences involving velar stops and velar fricatives in Polish, one would like to investigate if a fricative context also triggers allophonic retraction of /ɨ/. More data needs to be collected in order to form general conclusions regarding lip position. Finally, the temporal aspect of the vowels has not been investigated due to too low temporal resolution of the ultrasound recordings, but should be investigated in the future.

This study contributes to a better understanding of Polish phonology and phonetics, and it also provides insight into the broader problem of the articulatory phonetics of palatalization. In particular, the findings from the present study suggest that consideration of tongue root position should be integral to discussions of palatalization.

ACKNOWLEDGMENTS

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