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Articulatory characteristics of Hungarian 'transparent' vowels

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Abstract

Using a combination of magnetometry and ultrasound, we examined the articulatory characteristics of the so-called 'transparent' vowels [iː], [i], and [eː] in Hungarian vowel harmony. Phonologically, transparent vowels are front, but they can be followed by either front or back suffixes. However, a finer look reveals an underlying phonetic coherence in two respects. First, transparent vowels in back harmony contexts show a less advanced (more retracted) tongue body posture than phonemically identical vowels in front harmony contexts: e.g. [i] in *buli-val* is less advanced than [i] in *bili-vel.* Second, transparent vowels in monosyllabic stems selecting back suffixes are also less advanced than phonemically identical vowels in stems selecting front suffixes: e.g. [iː] in *ír*, taking back suffixes, compared to [iː] of *hír*, taking front suffixes, is less advanced when these stems are produced in bare form (no suffixes). We thus argue that the phonetic degree of tongue body horizontal position correlates with the phonological alternation in suffixes. A hypothesis that emerges from this work is that a plausible phonetic basis for transparency can be found in quantal characteristics of the relation between articulation and acoustics of transparent vowels. More broadly, the proposal is that the phonology of transparent vowels is better understood when their phonological patterning is studied together with their articulatory and acoustic characteristics.

1. Introduction

Since Öhman's (1966) seminal work on coarticulation in vowel–consonant–vowel (V–C–V) sequences, it is known that vowels exert influences on other vowels across intervening consonants. Such V-to-V coarticulation effects have been shown to depend on articulatory requirements of the intervening consonant(s) (see Recasens, 1999 for a review), distribution of stress (Fowler, 1983; Magen, 1997), and the segmental contrasts in the vowel inventory of a particular language (Beddor, Harnsberger, & Lindemann, 2002; Manuel, 1999). Despite such systematic variation, V-to-V coarticulation seems to be a universal property of speech and it is generally assumed to provide a natural phonetic basis for vowel harmony (Beddor, Krakow, & Lindemann, 2001; Fowler, 1983; Manuel, 1999; Ohala, 1994a, 1994b).

Many observed vowel harmony patterns can be plausibly related to V-to-V coarticulation effects between consecutive vowels. For example, the Hungarian dative suffix appears with a front [ɛ] or a back [ɔ] depending

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on the backness value of the vowels in the stem to which it attaches. Thus, a stem with back vowels like *város* [vɑːroʃ] 'city' selects a back suffix, *város-nak* [vɑːroʃnɔk] 'city-Dative', and a stem with front vowels like *öröm* [ørøm] 'joy' selects a front suffix, *öröm-nek* [ørømnɛk] 'joy-Dative'. In a large class of stems where stem-internal vowels disagree in backness, the quality of the suffix vowel is determined by the quality of the rightmost stem vowel: *béka-nak* [beːkɔnɔk] 'frog-Dative', *parfüm-nek* [pɔrfymnɛk] 'perfume-Dative'. Hence, the generalization is that suffix vowels receive their [±back] quality from the [±back] quality of the adjacent stem-final vowel. A phonetic basis for this generalization can be reasonably linked to V-to-V coarticulation effects between the contiguous stem-final and suffix vowels.

However, a productive group of stems challenges the well-cited view that V-to-V coarticulation provides a phonetic basis for vowel harmony. In these stems, the suffix vowel is not adjacent to the vowel that appears to determine its quality. For example, the dative suffix following stems such as *papír* [pɔpiːr] 'paper' takes on the [+back] value of the stem-initial vowel despite the [−back] quality of the intervening [iː]: *papír-nak* [pɔpiːrnɔk] 'paper-Dative'. The vowel [iː] is called transparent because it may intervene between the trigger and the target of harmony even though it bears the opposite value for the harmonizing feature. Effectively, then, vowels may establish harmony relations across not only consonants but also transparent vowels. Consequently, transparent vowels present a challenge to the proposal that vowel harmony has its basis in V-to-V coarticulation effects between consecutive vowels.

Previous studies carried out on languages without vowel harmony indicate that acoustic-perceptual patterns of V-to-V coarticulation may provide certain insights into the transparent behavior of non-low front vowels in languages with vowel harmony. For example, Recasens (1999) and Beddor et al. (2001) showed that under coarticulation with adjacent back vowels, [iː] is relatively stable both acoustically and perceptually. Hence, this stability of [iː] (i.e. the lack of F_2 lowering) might explain the fact that the adjacency of the front [iː] to the back [ɔ] in *papír* does not produce the fully harmonic outcome *[pɔpɯːr]. The fact that transparent vowels do not impart their phonetic quality on suffix vowels has also been traced to the coarticulatory properties of these vowels. Given the extreme values of F_2 for [i], Ohala (1994a, 1994b) has proposed that this vowel exerts a strong coarticulatory effect on its adjacent vowels such that "listeners would be most aware of such a phonetically mechanical effect and thus be able to parse it out of the signal" (Ohala, 1994a, p. 493).

Yet, other key aspects of the behavior of transparent vowels remain a puzzle. Consider, for example, the difference in the suffix vowels between words like *papír-nak* [pɔpiːrnɔk] 'paper-Dative' and *zefír-nek* [zɛfiːrnɛk] 'zephyr-Dative'. Clearly, the form of the suffix must be linked to the form of the stem-initial vowel. However, it is not clear how this can be achieved through the acoustic consequences of V-to-V coarticulation given that the stem-initial and suffix vowels are not adjacent. Although long-distance coarticulation across schwa was found in English (Magen, 1997), studies also show that [iː] is resistant to coarticulation from the preceding vowel(s) in terms of perception (e.g. Recasens, 1987 for Spanish and Catalan, Farnetani, Vagges, & Magno-Caldognetto, 1985 for Italian, Magen, 1984 for Japanese). Thus, the acoustic and perceptual stability of high front vowels does not fully explain the behavior of these vowels in vowel harmony.

In this paper, we turn to examine the articulatory properties of transparent vowels in an effort to elucidate a possible phonetic basis of transparency in vowel harmony. The results of our experiments show that sub-phonemic articulatory characteristics of transparent vowels systematically correlate with the [±back] form of the following suffix. Specifically, the main result is that continuous differences in the horizontal advancement of the tongue body in transparent vowels are linked to the alternations in suffix form: a more advanced transparent vowel is followed by a front suffix and a less advanced one is followed by a back suffix. In effect, the non-low front vowels in Hungarian are articulatorily permeable in the front-back dimension. When our articulatory results are combined with evidence from previous work on the perceptual stability of non-low front vowels, a phonetic basis for transparency becomes viable. Transparent vowels in palatal vowel harmony are those vowels that can be articulatorily retracted to a certain degree while still maintaining their front perceptual quality.

The paper is laid out as follows. Section 2 illustrates the phonological patterns of Hungarian transparent vowels in more detail and motivates this experimental study. Section 3 describes the experiments and the methodological issues related to data collection, quantification, and analysis. Section 4 presents the results of the experiments. Section 5 discusses the main findings and their relevance to the relationship between the phonetics and phonology of transparent vowels. Section 6 concludes with a summary of the main points.[2]

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[2] The presented data and its analysis draw from Benus (2005).

2. Transparency in Hungarian vowel harmony

Vowel harmony is a widespread pattern attested in many genetically unrelated languages, where vowels in some domain agree in one or more features. Most typically, in phonological terms, vowels harmonize with respect to the features corresponding to the horizontal or vertical position of the tongue body ('palatal' or 'height' harmony), the position of the tongue root ('ATR' harmony), or rounding of the lips ('labial' harmony). When harmony applies, all vowels in some relevant domain typically bear the harmonizing feature. This domain is usually restricted either in morphological or prosodic terms. In the most common cases, harmony applies within morphological words in that both stems and affixes participate (Anderson, 1980b; van der Hulst & van der Weijer, 1995). Vowel harmony has a similar function as stress in delimiting words (Trubetzkoy, 1939) and plays an active role in word-segmentation (Suomi, McQueen, & Cutler, 1997; Vroomen, Tuomainen, & Gelder, 1998). The Hungarian vowel inventory is summarized in (1), using Hungarian orthography and IPA symbols.

(1) Vowel inventory of Hungarian (Ringen & Vago, 1998)[3]

	[−back]				[+back]		
	[−round]		[+round]		[−round]	[+round]	
High	i [i]	i [iː]	ü [y]	ű [yː]		u [u]	ú [uː]
Mid	(e [ë])	é [eː]	ö [ø]	ő [øː]		o [o]	ó [oː]
Low	e [ɛ]				á [ɑː]	a [ɔ]	

The phonological effects of vowel harmony are most readily observed in suffix vowel alternations.[4] For example, in (2) the [±back] quality of various suffixes is determined by the [±back] quality of the preceding stem vowel (Siptár & Törkenzy, 2000; Vago, 1980; van der Hulst, 1985).

(2) Regular vowel harmony[5]

Front		Back	
vidék-től [videːktøːl]	country-Ablative	*város-tól* [vɑːroʃtoːl]	town-Ablative
öröm-nek [ørømnɛk]	joy-Dative	*mókus-nak* [moːkuʃnɔk]	squirrel-Dative
hegedű-nél [hɛgɛdyːneːl]	violin-Adessive	*harang-nál* [hɔrɔŋgnɑːl]	bell-Adessive
víz-ben [viːzbɛn]	water-Inessive	*ház-ban* [hɑːzbɔn]	house-Inessive

However, in Hungarian and other languages with vowel harmony, one also finds a set of so-called transparent vowels whose presence sometimes seems to have no effect on the choice of the suffix vowel. The examples in (3) show that the first stem vowel dictates the backness value for the suffix vowel across the intervening transparent vowels {[iː], [i], [eː]}. In the left column, stems with initial front vowels followed by a transparent vowel select front suffixes. In the right column, however, the initial stem vowel and the suffix vowel are back despite the front quality of the intervening transparent vowel. Hence, the initial and the suffix vowels are in a harmony relationship across both consonants and transparent vowels.

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[3] The mid short [ë] is a dialectal variant of low [ɛ] in several non-Budapest dialects.

[4] Stem-internal distributional patterns will not be discussed in this article. See Benus (2005) for a model of stem-internal harmony in Hungarian, and Kirchner (1999) or Harrison, Dras, and Kapicioglu (2002) for models of stem-internal harmony in Turkic languages.

[5] Hungarian has a rich system of morphological case marking. For example, for Nouns, in addition to the Nominative, Genitive, Accusative, Dative, or Instrumental cases, there are also cases that indicate spatial and kinetic conditions. For example, the Ablative case denotes 'from (nearby)', the Adessive 'at', and the Inessive 'in'.

(3) Harmony with stem-final transparent vowels

Front		Back	
emír-nek [ɛmiːrnɛk]	emir-Dative	*papír-nak* [pɔpiːrnɔk]	paper-Dative
zefír-ből [zɛfiːrbøːl]	zephyr-Elative	*zafír-ból* [zɔfiːrboːl]	sapphire-Elative
rövid-nek [røvidnɛk]	short-Dative	*gumi-nak* [ɡuminɔk]	rubber-Dative
bili-vel [bilivɛl]	pot-Instrumental	*buli-val* [bulivɔl]	party-Instrumental
művész-nek [myːveːsnɛk]	artist-Dative	*kávé-nak* [kɑːveːnɔk]	coffee-Dative
vidék-től [videːktøːl]	country-Ablative	*bódé-tól* [boːdeːtoːl]	hut-Ablative

Transparency in vowel harmony has been one of the core areas of phonological research (e.g. Anderson, 1980a; Anderson, 1980b; Archangeli & Pulleyblank, 1994; Clements, 1977; Kiparsky & Pajusalu, 2003; Ní Chiosáin & Padgett, 2001; Ringen, 1975; Smolensky, 1993; Vago, 1980; van der Hulst & Smith, 1986). For our purposes, the most relevant aspect of phonological treatments of transparency is that the agreement between the initial and the suffix vowels in words like *papír-nak* is made possible by marking the transparent vowel as 'invisible' to harmony. Such marking is motivated by theories of underspecification and markedness and is made possible by employing autosegmental representations, which effectively render adjacent the vowels surrounding the 'invisible' transparent vowel (van der Hulst & van der Weijer, 1995; Steriade, 1995 for reviews).

In several studies, phonetic characteristics of transparent vowels have been explicitly invoked to motivate the assumed non-participation of these vowels in harmony (Baković & Wilson, 2000; Gafos, 1999; Kaun, 1995; Ní Chiosáin & Padgett, 2001). However, these studies do not use experimental methods to support the assumptions of their theoretical proposals. In more recent experimental work, the assumption that transparent vowels do not participate in harmony has been questioned. See Benus, Gafos, & Goldstein (2003) and Benus & Gafos (2005) on Hungarian palatal harmony and Gick, Pulleyblank, Campbell, & Mutaka (2006) on Kinande ATR harmony.

In sum, despite the wealth of research on the phonological patterning of transparent vowels, relatively little attention has been devoted to their phonetics. The experimental investigations on the acoustic and perceptual resistance to coarticulation of [i], [e] (e.g. Beddor et al., 2001), though plausibly related to the nature of transparency, were conducted on languages that do not exhibit vowel harmony. The available experimental studies in languages with palatal vowel harmony are limited in both number and scope and investigate only the acoustics of these vowels (Gordon, 1999; Välimaa-Blum, 1999).

In this paper, our main aim is to provide a first detailed articulatory description of transparent vowels in palatal vowel harmony.

3. Methodology

To study the articulatory characteristics of transparent vowels, we recorded movements of the tongue body, the primary articulator in the production of vowels and a major determinant of their acoustic output. There are two available experimental techniques for the observation of tongue body movements (Stone, 1997 and references therein). The first is imaging of a limited number of tongue flesh-points using either an electromagnetic or an X-ray field. The second is imaging of the global tongue surface using ultrasound or magnetic resonance imagery. In this study, we combined a flesh-point imaging (electromagnetometry) with a global imaging technique (ultrasound) in an attempt to collect comprehensive information on the articulatory properties of transparent vowels.

3.1. Electromagnetometry and ultrasound

Electromagnetic midsagittal articulometry (EMMA; Perkell et al., 1992; Stone, 1997) allows us to track the movements of small receivers attached to the speech articulators.[6] In this study, 8 such receivers were placed in

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[6] Standard calibration and cleaning procedures for each of these receivers were completed before each experiment (Kaburagi & Honda, 1997).

a mid-sagittal plane on the nose, maxilla, upper lip, lower lip, jaw, tongue body (2), and tongue dorsum. The position of the receivers in a two-dimensional (2D) coordinate plane as a function of time was calculated using the voltages in the receivers that were captured with the use of specialized software (Tiede, Vatikiotis-Bateson, Hoole, & Yehia, 1999) at a sampling rate of 500 Hz. Audio data were also collected with a Sennheiser shotgun microphone at a sampling rate of 20 kHz.

The ultrasound technique allows imaging of the surface of the tongue (Stone, 1997, 2005). A subject places the ultrasound probe sagittally below his/her chin, in the soft area surrounded by the jawbone. A piezoelectric crystal in the probe emits ultra-high frequency waves and receives the reflected echo. The emitted waves travel through the soft tissue of the tongue and reflect when they reach an interface with a matter of different density such as bone or air. This echo is used to construct a bright white line tracing the boundary between the tongue surface and the air above it. The sagittal placement of the probe provides images of the mid-line of the tongue from the tongue blade to the tongue root.

An ALOKA SSD-1000 ultrasound system at Haskins Laboratories with a 3–5 MHz convex-curved probe was used. Ultrasound images of the tongue were collected at a 30 Hz rate, recorded on an S-VHS video-recorder, and digitized into sequences of images in the 'jpeg' format.

During data collection, the movement of the subject's head with respect to EMMA's transmitter coils and the ultrasound probe must be minimized to allow for the comparison of data across tokens. Large-scale movements were successfully prevented by the headband apparatus for magnetometry, and for ultrasound by positioning the head against a headrest and instructing subjects not to move their heads during data collection.

To correct for inevitable minor head movements, data from the receivers placed on the nose and maxilla (the gum above the upper front teeth) were used. The movement of these two receivers does not result from speech articulation but from the minor head movements within the helmet. Hence, the time-varying data on the position of the receivers placed on the active articulators (e.g. the tongue) were corrected for head movement using the movement data from the nose and the maxilla receivers.

To limit movement of the subjects' head in relation to the ultrasound probe, two elastic self-adhesive bands were attached to the probe and then wrapped around the subject's head. In addition, the sides of the probe were taped on the subject's skin. In this way, the probe was fixed to the subject's jaw so that it moved together with the subject's head. Due to the elasticity of the adhesive bands, the movement of the jaw was not substantially restricted.[7]

3.2. Stimuli and subjects

In describing our stimuli, we classify stems in terms of their harmonic type. There are two harmonic types, front and back. A stem is of the front harmonic type when it selects suffixes with [−back] vowels and it is of the back harmonic type when it selects suffixes with [+back] vowels. The effect of harmonic type on the production of transparent vowels was investigated by comparing tongue body position during transparent vowels across stems of the two harmonic types. For this purpose, the stimuli consisted of lexical pairs, e.g. *bili̲-vel* [bilivɛl] 'pot-Instrumental' vs. *buli̲-val* [bulivɔl] 'party-Instrumental'.

Within lexical pairs, significant effort was made to control for the consonants surrounding the transparent vowels so that the effect of harmonic type on the production of transparent vowels was not obscured by spurious consonantal differences. Thus, consonants surrounding the transparent vowels in the two members of each lexical pair were as similar as possible. Ideally, both preceding and following consonants were identical, as in *bulival* [bulivɔl] vs. *bilivel* [bilivɛl], or they agreed in the place of articulation, as in *tömítő* [tømiːtøː] vs. *tompító* [tompiːtoː]. In addition, transparent vowels in open syllables were preferred due to the assumption that coda consonants interfere with the preceding vowel more than the following onset consonants. Dorsal and lateral consonants were avoided in the position following the transparent vowels whereas labials, labiodentals, and the glottal [ɦ] were preferred to coronals. This is because labials, labiodentals and glottals have a much smaller effect of the tongue body and dorsum position than velars or the lateral [l]. Attention was also paid to the prosodic structure so that the distribution of long and short

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[7] See Stone (2005) and Gick (2002) on other head stabilization methods for ultrasound data collection.

consonants and vowels between the two members of each lexical pair was as similar as possible.[8] Finally, morphological structure had to be considered as well. Hungarian has a significant number of compounds and verbal prefixes that were avoided because a boundary between two members of a compound or between a prefix and a verb blocks harmony in Hungarian (e.g. Vago, 1980, p. 27). Although harmony is pervasive in verbs, nouns and adjectives alike, effort was made to keep the part of the speech identical for both members of a lexical pair.

It was impossible to create a list of real-word stimuli that simultaneously satisfied all the above considerations, and provided a sufficiently large number of lexical pairs to represent the general pattern of vowel harmony. However, attention to both of these criteria was paid as much as possible with the aim to create a sufficiently controlled and representative stimuli list. Appendix A contains the complete list of stimuli.

Two sets of stimuli were constructed. In the first set, transparent vowels occurred in disyllabic stems such as *buli* vs. *bili*, and were followed by a monosyllabic suffix. This approach yielded trisyllabic words, a sample of which is given in (4).

(4) Examples from the first set of stimuli—disyllabic stems with suffixes

Front		Back		Suffix
zefír-ben [zefiːrbɛn]	‘zephyr’	*zafír-ban* [zɔfiːrbɔn]	‘saphire’	Inessive
bili-vel [bilivɛl]	‘pot’	*buli-val* [bulivɔl]	‘party’	Instrumental
bidé-től [bideːtøːl]	‘bidet’	*bódé-tól* [boːdeːtoːl]	‘hut’	Ablative

The transparent vowels in all stimuli of this set were surrounded by either front vowels or back vowels. Therefore, it is plausible to expect that the surrounding vowels influence the production of transparent vowels via coarticulation. As a result, one might expect that the transparent vowels surrounded by back vowels will be produced more retracted compared to the phonemically identical vowels surrounded by front vowels.

In the second set of stimuli, transparent vowels in the front- and back-selecting stems were not adjacent to any other vowels. This set was constructed using two crucial properties of Hungarian morphology. First, a limited number of monosyllabic stems containing a transparent vowel (T stems) select back suffixes whereas all other T stems select front suffixes. Second, certain morphological categories such as the nominative singular for nouns and the third person singular for verbs are marked with phonologically zero suffixes. Combining these two properties allows us to create monosyllabic stimuli of both the front and the back harmonic type with no additional vowels present. A sample from the second stimuli set is shown in (5).

(5) Examples from the second set of stimuli—monosyllabic stems without suffixes

Front		Back	
ív [iːv]	‘bow’	*vív* [viːv]	‘fence’
hír [ɦiːr]	‘rumor’	*ír* [iːr]	‘write’
szél [seːl]	‘wind’	*cél* [t͡seːl]	‘aim’
éj [eːj]	‘night’	*héj* [ɦeːj]	‘crust’

The two stimuli sets had different sizes. There were 22 pairs and 8 repetitions of each word for the trisyllables, but only 8 pairs and 4 repetitions for the monosyllables. The distribution of transparent vowels in the trisyllabic lexical pairs was balanced: 7 pairs with [iː], 8 pairs with [i], and 7 pairs with [eː]. This balance was not achieved in the monosyllabic stimuli which consisted of 5 pairs with [iː], 1 pair with [i], and 2 pairs with [eː]. The decreased number of pairs in the second set is a consequence of the relatively limited number of monosyllabic stems that select back suffixes, and the constraint to maintain minimal consonantal differences between the members of each pair. The bias for stems with [iː] in the monosyllabic set reflects the distribution

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[8] Hungarian stress falls on the leftmost syllable irrespective of syllable weight (Siptár & Törkenzy, 2000).

of these vowels in the Hungarian lexicon. A search of an electronic Hungarian lexicon (Füredi, Kornai, & Prószéky, 2004) reveals that of 24 monosyllabic noun stems with transparent vowels that take back suffixes, 19 contain /í/, 3 contain /i/ and 2 contain /é/.

All stimuli were embedded in the frame sentence: Azt mondom, hogy _____ és elismétlem azt, hogy _____ mégegyszer [ɔztmondomɦoɟ _____ eːʃɛliʃmeːtlɛmɔztɦoɟ _____ meːgɛɟsɛr] ‘I say and I repeat once again’.[9] This generated two renditions of the token in each sentence.[10] The sentences were randomized and presented to subjects visually on a computer screen.

The results from three subjects are presented. All of them were young adults in their twenties and identified themselves as speakers of the Budapest dialect. ZZ (male) and BU (female) were presented with the most complete set of stimuli that was described above (Appendix A). CK (female) was the pilot subject with whom a slightly different set of stimuli and one additional frame sentence was used (Appendix B).

3.3. Data collection and measurements

We collected 8 repetitions of 44 lexical items (22 pairs) of trisyllabic words in 2 positions with subjects ZZ and BU, which yielded a total of 704 tokens for each subject. After excluding corrupted data, a total of 664 tokens for ZZ, and 658 for BU were analyzed. We also collected 4 repetitions of 16 lexical items (8 pairs) of monosyllabic words in 2 positions. This gave a total of 128 analyzed tokens. For ZZ and BU, three tongue receivers were used: two on the tongue body (TB1, TB2), and one on the tongue dorsum (TD). For the pilot subject CK, 4 repetitions of 64 lexical pairs in 2 harmonic types generated a total of 512 collected tokens, out of which 494 were analyzed. Additionally, 4 repetitions of 3 lexical pairs, giving a total of 24 tokens of monosyllabic stems were collected. For CK, receivers on the tongue tip (TT), tongue body (TB), and tongue dorsum (TD) were used.

Ultrasound data from one subject (ZZ) were collected using the same stimuli as for the EMMA method. The stimuli were divided into two separately randomized blocks but the data from the two blocks were not collapsed. This is because the elastic bands that ascertain the fixed placement of the probe with respect to the subject’s head were taken off after the first block of data was collected. Although an effort was made to reattach the probe on the same location of the subject’s under-chin, there would be no objective means to evaluate our success.

EMMA data were quantified with the use of a Matlab-based tool called MAVIS (Tiede et al., 1999). In a palatal vowel harmony system like that of Hungarian, vowel harmony primarily entails displacements of the tongue along the horizontal or front–back axis. Hence, we assessed the degree of participation of a transparent vowel in harmony by measuring the extreme front position of tongue body during the transparent vowel.

Fig. 1 shows a representative EMMA recording and illustrates the quantification procedure. As the tongue body smoothly moves from vowel to vowel in the sequence [ɔ–iː–ɔ] *of zafírban*, the TB, TD receivers can be seen to trace a bell-shaped trajectory from a retracted position for [ɔ], with low horizontal values of TB and TD, to an advanced position for [iː], with higher horizontal positions for TB and TD, and back to a retracted position of the final [ɔ].

To quantify spatial properties of transparent vowels we first manually identified the transparent vowel in each token using auditory and articulatory information. Then, we determined the maximal horizontal positions of the TB, TD receivers during that vowel using an automatic procedure that detects peaks of the time functions representing the kinematic trajectories of the receivers.[11] These peaks are shown as the ‘max’ labels in Fig. 1. We then extracted the spatial (horizontal) value of the receiver at the labeled time points. A statistically significant difference between these values from the front and back harmonic types would indicate a significant effect of the harmonic type on the position of the tongue receivers, and hence, on the position of the tongue body.

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[9] The IPA transcription is a broad phonemic transcription.

[10] A statistical analysis of stimulus position in the frame sentence revealed no significant effect on the horizontal position of the tongue. Hence, in the discussion of results, the values from the two positions were pooled.

[11] In some cases, the horizontal movement of the tongue was smooth during the acoustic portion of the transparent vowel without any peak. In these cases, the ‘max’ labels were placed at the point of maximal front position within the acoustic portion of the vowel. Usually, this point was around the release of the preceding consonant.

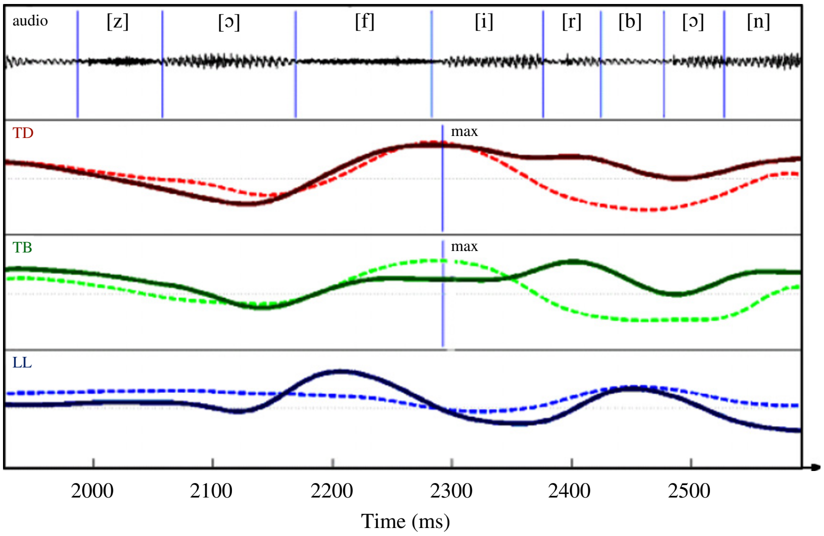

Fig. 1. Articulatory kinematics of the word ‘zafírban’ recorded with EMMA. The top panel represents the acoustic waveform. The bottom three panels represent the vertical (solid curve) and horizontal (dashed curve) position of the receivers attached on the tongue dorsum (TD), tongue body (TB), and lower lip (LL).

Ultrasound data were quantified using Matlab procedures developed by Iskarous (2005). Because the vowel gesture spans several individual frames, the frame with the most advanced position of the tongue body was determined as the target frame. This was done manually, using both visual and acoustic information. Then, the tongue edge in this target frame was traced using the semi-automatic procedure described in Iskarous (2005). All the curves representing the tongue edge were normalized to 100 points. Given effective measures for preventing head movement with respect to the probe, the two-dimensional (2D) coordinates of these points represent the position of the mid-sagittal tongue section in an arbitrary, but fixed, coordinate system.

To quantify the effect of harmonic type, two types of data were extracted. First, a pair-wise comparison of the curves was performed by calculating the area between the curves.[12] The effect of harmonic type on tongue shape is significant if the area values between the pairs of curves from the same type (front–front, back–back) are significantly smaller than the area values between the pairs of curves from the opposing types (front–back). For example, each lexical item was repeated 8 times in one block, and because the harmonic type condition is binary (front vs. back), the available data consists of 8 curves from the front harmonic type words and 8 from the back harmonic type words. A pair-wise comparison where one curve is from the front type and the other from the back type yields 64 combinations. A pair-wise comparison where the two curves come from the same type yields 56 combinations (28 for both front–front and back–back). If the area values of the 64 comparisons across the types are significantly greater than the area values of the 56 comparisons within the types, the effect of harmonic type is considered significant.

Importantly, the length of the curves potentially affects the area between them. This is because two very similar long curves can have a greater area than two short but less similar curves. In order to control for the effect of the length, the endpoints of the shortest curve in the set of curves under investigation were determined and then used to define the angle AOB sketched in Fig. 2. The origin O is a fixed point relative to the ultrasound transducer, and A–B are the endpoints that produce the smallest value of the angle γ for a particular lexical item. The area between the two curves defined by the angle γ was then calculated.

The area measure determines only the significance of the harmonic type with respect to the global shape of the tongue, but not the more specific issue of whether the tongue is more retracted in the back harmonic type words than in the front harmonic type words. In order to determine the size and direction of the differences between the tongue shapes, a second quantification method for ultrasound data was devised. In this method,

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[12] We are grateful to David Goldberg and Lisa Davidson for help and discussions on this issue. See Davidson (2005) for similar pair-wise comparison using L2-norms instead of area.

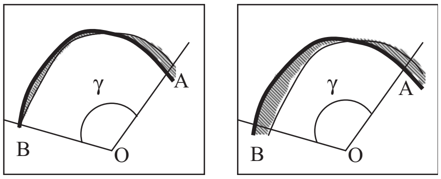

Fig. 2. Comparison of two curves as the difference in the area between them. The tongue tip is on the right.

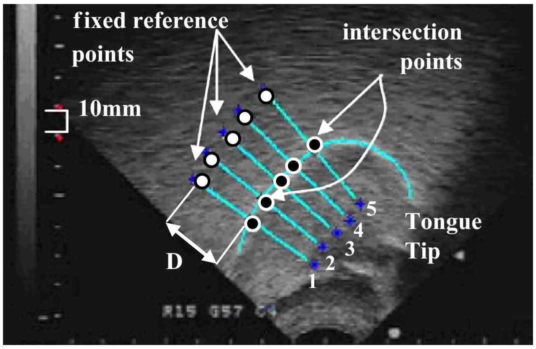

Fig. 3. Quantification of the effect of harmonic type from the ultrasound images. The white bi-directional arrow shows the distance *D* between the fixed points of the line marked with white dots and the corresponding intersection points marked with black dots.

five fixed reference lines were superimposed on each target frame.[13] To maximize the information obtained by combining EMMA and ultrasound, these lines were placed in the posterior area of the tongue which is not accessible with EMMA. Keeping the lines constant across all tokens, the distance *D* in millimeters between the fixed reference point at the beginning of each line and the point where that line intersects the tongue's surface was computed. This is illustrated in Fig. 3. The resulting distances give a relative measure of the degree of advancement in the dorso-pharyngeal area of the tongue.

3.4. Comparison of the magnetometry and ultrasound techniques

The EMMA and ultrasound techniques complement each other, providing comprehensive information about the articulatory characteristics of transparent vowels. EMMA's advantage is that it offers highly precise temporal and spatial information about the movements of particular points on the tongue. Its disadvantage is the limited number of these points. The tongue is a complex organ and the 2D information about the movement of 3–4 flesh points provides only a crude picture of vowel production. Furthermore, with the EMMA technique it is difficult to acquire information about the action of the tongue behind the dorsal area. This is due to the gag reflex that prevents subjects from tolerating objects placed in the back of the tongue.

Ultrasound compensates for EMMA's weakness by providing global images of (almost) the complete surface of the tongue. However, compared to EMMA's high precision, the spatio-temporal information in ultrasound is limited. In the temporal domain, ultrasound's sampling rate was 30 Hz compared with EMMA's 500 Hz. In the spatial domain, EMMA's measurement error is within .5 mm (Perkell et al., 1992) but the actual error in the measurements such as the one reported in this experiment is even less than .5 mm (Hoole & Nguyen, 1997). Ultrasound accuracy approaches 1 mm, in part due to artifacts in the noisy image (Stone, 2005).

In addition, the quantification of the effect of harmonic type on the position of the tongue differs between the two techniques. In this study, for the EMMA data, the effect of harmonic type is quantified as differences in the horizontal position of the tongue receivers. For the ultrasound data, retraction is calculated on planes

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[13] We are grateful to Khalil Iskarous for help with and discussion on this method.

that are not strictly horizontal. As can be seen in Fig. 3, the fixed reference lines used for measuring the distances are not at 180° but somewhere between 130° and 150°. This means that the distances measured using the fixed lines have both a horizontal and a vertical component. It may be argued that this ultrasound quantification method better captures the action of the tongue muscles in creating specific tongue shapes. In our case, tongue body retraction results from the action of the styloglossus, raising the tongue dorsum towards the velum, and the posterior verticalis that constricts to flatten the tongue body in the back of the tongue (e.g. MacKay, 1987).

Finally, the three described quantification methods—horizontal position of three tongue flesh points with EMMA, distance measured using intersection points between the tongue surface and fixed reference lines with ultrasound, and the area measure with ultrasound—provide a continuum between local and global information about the tongue position. The quantification of the EMMA data provides the most local information because the three flesh points on the tongue are fixed and thus it is only information about the movement of three fixed points that is obtained. The ultrasound measure using intersection points is less local because, instead of a point on the tongue, what is fixed is the position of a reference line. Hence, the actual intersection point of the tongue edge with that reference line corresponds to potentially different points on the tongue for every target frame. As a result, this second measure provides information about the position of a number of tongue points within the fixed range delimited by the five reference lines. Finally, the ultrasound area measure is the most global one since it uses almost the entire tongue shape and there are no fixed points or lines.

Overall, then, the combination of the two techniques and their respective quantification methods offers highly informative data on the articulation of transparent vowels.

3.5. Statistical analysis

For the purposes of the statistical analysis, the EMMA data were structured in the following way. For subjects ZZ and BU there were three dependent variables: TD, TB2, and TB1. These represent the MAX values (the most front position of the receiver) measured with the receivers placed at the tongue dorsum, posterior tongue body, and anterior tongue body, respectively. For subject CK, there were only two dependent variables, TD and TB. Additionally, there were two independent variables for each subject: H-TYPE representing front or back harmonic type, and VOWEL representing the three transparent vowels {[iː], [i], [eː]}.[14] The EMMA data are analyzed separately for each subject because receiver placement (dependent variables) is particular to each subject.

For ZZ's ultrasound data, there were two dependent variables: AREA, representing the area between a pair of tongue shapes, and DISTANCE, the distance between the endpoint of a fixed line and the intersection of that line with the tongue shape illustrated in Fig. 3. In addition to H-TYPE and VOWEL from the EMMA data, the independent variable BLOCK is included.

The statistical analysis of the data was primarily based on analysis of variance tests (ANOVA) performed with the software package SPSS.

4. Results

4.1. Trisyllabic words

We first report the results for the effect of harmonic type, followed by the interactions between harmonic type and vowel category (H-TYPE*VOWEL).

4.1.1. Effect of harmonic type: EMMA

One-way anova tests showed that harmonic type significantly affected the position of the receivers placed on the tongue. This was the case for all three receivers for subject ZZ ($F(1,662) = 62.288$, $p < .001$ for TD; $F(1,662) = 57.065$, $p < .001$ for TB2; $F(1,662) = 45.835$, $p < .001$ for TB1) and subject BU ($F(1,680) = 15.856$,

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[14] VOWEL includes the low [ɛ] for the pilot subject CK.

Table 1
Direction and size of the effect of harmonic type

Rec.	ZZ			BU			CK		
	F	B	MD	F	B	MD	F	B	MD
TD	−48.02	−48.97	.95*	−43.12	−43.51	.39*	−24.59	−25.58	.99*
TB2	−38.65	−40.05	1.40*	−30.89	−31.48	.59*			
TB1	−23.41	−24.73	1.32*	−21.68	−22.07	.39*	−21.83	−22.08	.23

Mean difference (MD) = Front (F)−Back (B).

$p<.001$ for TD; $F(1,680) = 29.141$, $p<.001$ for TB2; $F(1,680) = 14.035$, $p<.001$ for TB1). For the pilot subject CK, the effect of harmonic type was significant in one out of two receivers ($F(1,472) = 8.348$, $p = .004$ for TD, $F(1,491) = .748$, $p = .388$ for TB).

Data in Table 1 show the size and the direction of the effect that harmonic type had on the horizontal position of the vowels. The values in the columns labeled F and B are the means of the horizontal maxima of the receivers during the transparent vowels occurring in the words of the front and back harmonic type, respectively, and they are shown in millimeters.[15] The values in the MD column represent the difference between the mean values for the position of the receivers in the two harmonic types. The absolute value of MD thus corresponds to the size of the effect, and its sign shows the direction of the effect. If the MD value is positive (negative), the relevant receiver is more (less) advanced in the transparent vowels of the front harmonic type words than in the transparent vowels of the back harmonic type words.

All MD values in Table 1 are positive, which means that the transparent vowels were more advanced in the front harmonic type words than in the back harmonic type words. Given the significance of H-TYPE in the reported Anova tests, it can be concluded that transparent vowels occurring in the front harmony type words were produced with significantly greater advancement than the vowels occurring in the back harmony type words by all three subjects.

4.1.2. Effect of harmonic type: ultrasound

Extraction of the tongue edge using ultrasound provides another way to compare the tongue body posture of transparent vowels across harmonic types. Fig. 4 shows two representative examples of such a comparison. Visual inspection of the plots indicates the same main result as in the EMMA data: transparent vowels in the front harmony type words (light solid lines) were more advanced than those in the back harmony type words (bold dashed lines). The greatest difference between the shapes from the two harmonic types was observed in the posterior area of the tongue.

Following the discussion in Section 3.3, we quantified this effect in two ways. First, we calculated the area between tongue shapes (AREA). One-way anova revealed that the curves from the same harmonic types were significantly more similar than the curves from the different harmonic types ($F(1,2638) = 280.294$, $p<.001$ for Block 1, $F(1,2518) = 570.229$, $p<.001$ for Block 2). In both blocks, the area was greater for the curves extracted from different harmonic types than for the curves extracted from the same harmonic types (964.6 vs. 706.5 in Block 1, 1171.2 vs. 749.5 in Block 2).[16] Therefore, harmonic type has a significant effect on the position of the tongue.

Second, we calculated tongue retraction measured along five fixed lines in a 2D reconstruction of the tongue edge. The effect of harmonic type was highly significant ($p<.0001$) for all five lines in both blocks. To determine the size and the direction of this effect, the mean difference (MD) between values in the front and

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[15] All MAX values are negative due to a convention that the zero of the horizontal axis in calculating EMMA output is above the front incisors (the maxilla receiver). The receivers toward the outside of the vocal tract, such as those on the lips, get assigned positive values whereas those inside the vocal tract get negative values. Hence, the greater the absolute value in the F and B columns, the more retracted is the horizontal position of the corresponding receiver.

[16] The area calculation was performed in pixels.

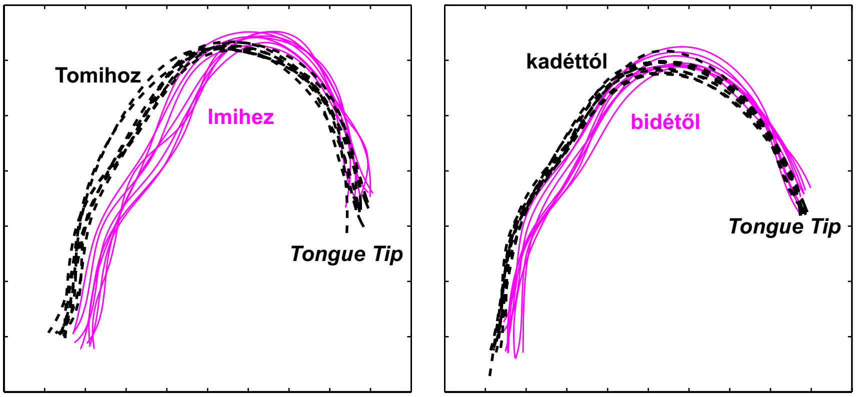

Fig. 4. Cross-sectional outline of the tongue in Tomihoz vs. Imihez (left) and kadéttól vs. bidétől (right) in back (dotted) and front (solid) harmony type. There are 8 tokens for each word; the *x*- and *y*-axis units represent an arbitrary but fixed coordinate system.

Table 2
Mean difference (MD) in mm between the tongue shapes from the front and back harmonic type

Block	$\mathrm{MD} = D_{\mathrm{Front}} - D_{\mathrm{Back}}$				
	Line-1	Line-2	Line-3	Line-4	Line-5
1	1.15*	1.74*	1.92*	1.63*	.74*
2	1.57*	2.17*	2.5*	2.34*	1.58*

'*' marks a significant effect of harmonic type.

back harmonic types were computed from the mean *D* values for each line. Table 2 shows the results with the MD values in millimeters.

All the MD values were positive, which shows that the transparent vowels in the front harmonic type words were more advanced than in the back harmonic type words. Harmonic type had the greatest effect on the middle Line-3 where it reached 2.5 mm, and the effect was gradually scaled down towards the peripheral Lines 1 and 5. Data in Block 2 showed a consistently greater effect of harmonic type on all lines than data in Block 1, which can presumably be attributed to the differences in the placement of the ultrasound probe between the two blocks.

To summarize, measurements of tongue position with ultrasound support the main result obtained from EMMA that transparent vowels in the front harmonic type words were more advanced than in the back harmonic type words.

4.1.3. Interaction of harmonic type and vowel: EMMA

Vowel category showed a significant effect on the position of all tongue receivers for all subjects in all tests. Two-way anova tests summarized in Table 3 revealed that the interaction between harmonic type and vowel was significant for subject ZZ, but not for BU. For subject CK, the interaction reached tendency ($p = .061$) in receiver TB.

Table 4 shows that with the exception of CK's [i] data measured with TB, the MD values for the individual transparent vowels were all positive. This means that each transparent vowel was less advanced in the back harmony type words than in the front harmony type words. Additionally, the stimuli for subject CK also included a limited number of tokens where the transparent vowel was the short low [ɛ]. The effect of harmony type on the horizontal position of [ɛ] when it behaves transparently (a back suffix follows) was consistent with the rest of the data: [ɛ] was more advanced in the front harmony type words (e.g. *érem-nek* [eːrɛmnɛk], *tetem-nek* [tɛtɛmnɛk]) than in the back harmony type words (e.g. *hárem-nak* [ɦɑːrɛmnɔk], *totem-nak* [totɛmnɔk]).

Given the significance of the interaction between harmonic type and vowel category for ZZ reported in Table 3, we explored in more detail how harmonic type affected the horizontal position of the individual transparent vowels for this subject. Table 4 shows that the back harmonic type [eː] was retracted the most, followed by [i], and the smallest retraction is observed for the vowel [iː]. This generalization applied to all three receivers for ZZ. In the two harmonic types separately, there were significant effects for VOWEL on all three receivers, which is reported in Table 5. The post hoc Tukey HSD tests ($\alpha = .05$) were conducted to examine how individual vowels contributed to the overall significance of VOWEL. These tests revealed that in the front harmonic type, [i] and [iː] were not significantly different from each other for TD and TB2 receivers and that [eː] was not significantly different from [iː] for all receivers in the back harmonic type. All other comparisons revealed significant differences. The post hoc tests are summarized in Appendix C.

Table 3
Interaction of harmonic type and vowel (two-way anova)

Subject	Receiver	Type III SS	df	df (error)	Mean square	*F*	Sig.
ZZ	TD	14.832	2	622	7.416	3.304	.037
	TB2	58.382	2	622	29.191	5.826	.003
	TB1	101.428	2	622	50.714	8.791	.000
BU	TD	.384	2	676	.192	.121	.886
	TB2	7.43	2	676	3.715	1.961	.142
	TB1	2.324	2	676	1.162	.667	.514
CK	TD	22.425	3	465	7.475	1.243	.294
	TB	36.281	3	465	12.094	2.472	.061

Table 4
Degree of advancement for individual transparent vowels in the front (F) and back (B) harmony type words, MD = F–B

	Rec	[i]			[iː]			[eː]			[ɛ]		
		F	B	MD	F	B	MD	F	B	MD	F	B	MD
ZZ	TD	−48.27	−49.26	.99	−48.50	−49.07	.56	−47.28	−48.57	1.29			
	TB2	−39.45	−40.98	1.53	−39.16	−39.73	.59	−37.39	−39.41	2.01			
	TB1	−24.31	−25.70	1.39	−23.53	−23.84	.31	−22.42	−24.63	2.22			
BU	TD	−43.53	−43.89	.37	−42.80	−43.15	.36	−42.99	−43.45	.46			
	TB2	−31.40	−31.91	.51	−30.64	−31.03	.38	−30.55	−31.43	.88			
	TB1	−22.20	−22.53	.34	−21.15	−21.43	.28	−21.62	−22.19	.56			
CK	TD	−22.41	−22.93	.52	−25.63	−25.91	.28	−23.24	−24.56	1.32	−31.87	−32.76	.89
	TB	−20.12	−19.74	−.38	−22.74	−22.93	.19	−20.50	−20.94	.44	−26.53	−27.35	.82

All values are in millimeters.

Table 5
Effect of vowel category in the front and back harmonic types separately, subject ZZ

Subject	Source	Grouping	Receiver	df (between)	df (within)	MS	*F*	Sig.
ZZ	VOWEL	H-TYPE FRONT	TD	2	329	47.069	23.360	.000
			TB2	2	329	137.299	28.867	.000
			TB1	2	329	100.638	19.172	.000
		H-TYPE BACK	TD	2	329	13.912	5.609	.004
			TB2	2	329	77.233	14.699	.000
			TB1	2	329	97.416	15.478	.000

The combination of these observations and the values in Table 4 leads to the conclusion that in ZZ's data the harmonic type affected the horizontal position of [eː] significantly more than for [iː]. This is inferred from the fact that [eː] was significantly more advanced than [iː] in the front harmony type words but not so in the back harmony type words. In addition, the effect of harmony type was significantly different for [iː] and [i]. This was inferred from the fact that [i] and [iː] were not significantly different in the front harmony type words, but [iː] was significantly more advanced than [i] in the back harmony type words. The EMMA data thus showed the continuum [eː] > [i] > [iː] in the degree by which harmonic type affected the horizontal position of the individual vowels.

4.1.4. *Interaction of harmonic type and vowel: ultrasound*

Given the significance of harmonic type in the ultrasound data reported in Section 4.1.2, Table 6 reveals that both VOWEL as well as the interaction H-TYPE*VOWEL had a significant effect on both dependent variables.[17]

Table 7 shows the size and the direction of the effect of harmonic type for the three vowels separately. It can be seen that all the MD values except one ([eː], Line-5, Block1) were positive. This shows that transparent

Table 6
Interaction of harmonic type and vowel category in the ultrasound data (two-way Anova)

Dep. var.	Source	Block	Type III SS	df	Mean square	*F*	Sig.
DISTANCE	VOWEL	1	1.075	2	.537	11.600	.000
		2	.999	2	.499	12.194	.000
	H-TYPE *VOWEL	1	1.814	2	.907	19.573	.000
		2	1.092	2	.546	13.328	.000
	ERROR	1	81.270	1754	.046		
		2	71.415	1744	.041		
AREA	VOWEL	1	4,332,055.976	2	2,166,027.988	14.064	.000
		2	5,384,985.481	2	2,692,492.741	14.077	.000
	H-TYPE *VOWEL	1	1,578,705.726	2	789,352.863	5.125	.006
		2	5,760,042.769	2	2,880,021.384	15.057	.000
	ERROR	1	405,660,036.963	2634	154,009.126		
		2	480,848,412.053	2514	191,268.263		

Table 7
Mean difference (MD) in mm between the tongue shapes from the front and back harmony type words, and mean area (AREA) between the curves from the same and different harmonic types

Block	Vowel	MD = $D_{\text{Front}} - D_{\text{Back}}$						AREA	
		Line-1	Line-2	Line-3	Line-4	Line-5	Total	Same	Different
1	[i:]	1.4	2.34	2.79	2.35	1.24	2.03	734.3	1022.8
	[i]	1.34	1.97	2.19	2.12	1.03	1.73	700.0	994.3
	[e:]	.69	.87	.74	.36	−.09	.51	686.0	872.4
2	[i:]	1.92	2.68	3.05	2.94	2.07	2.53	684.1	1209.1
	[i]	1.48	2.27	2.92	2.7	1.69	2.21	799.8	1245.6
	[e:]	1.31	1.54	1.5	1.34	.97	1.33	764.7	1058.8

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[17] The data from the five lines were pooled for this test. Although both H-TYPE and VOWEL interacted significantly with LINE, the three-way interaction was not significant.

vowels in the front harmony type words were more advanced than in the back harmony type words. This conclusion was also supported by the Area measure: in all cases, the mean area between two curves drawn from opposite harmonic types was larger than when the curves were drawn from the same harmonic type.

With respect to individual vowels, the effect of harmonic type was greatest for [iː] where it reached up to 2.5 mm on average in Block 2. The smallest effect was observed with [eː]. Hence, the ultrasound data revealed the continuum [iː]>[i]>[eː] in the degree to which harmonic type affected the tongue position of the transparent vowels.

Similarly to the EMMA data, VOWEL was significant in the two harmonic types separately, $F(2, 1757) = 33.615$, $p < .001$ in the front harmonic type, and $F(2, 1747) = 7.728$, $p < .001$ in the back harmonic type for the MD variable. The post hoc Tukey HSD tests ($\alpha = .05$) revealed that in the front harmonic type, all three vowels were significantly different from each other. In the back harmonic type, [eː] was not significantly different from [iː] but both differed significantly from [i]. The post hoc tests are summarized in Appendix C. These results, together with the observation that in the front harmonic type [iː] was more advanced than [eː] (mean difference of 1.2 mm) show that harmonic type affected the horizontal position of [iː] significantly more than the horizontal position of [eː]. This is inferred from the fact that [iː] was significantly more advanced than [eː] in the front harmonic type but not so in the back harmonic type.

4.1.5. Summary of trisyllabic data

The main finding is that transparent vowels were significantly more retracted in the back harmonic type words (e.g. [bul**i**vɔl]) than in the front harmonic type words (e.g. [bil**i**vɛl]). This effect was robustly present in all three subjects and both methodologies. In addition, harmonic type affected individual transparent vowels to a different degree. In the region of the tongue body below the palatal area, as measured with EMMA, the differences in the horizontal position of the tongue between the two harmonic types was greater for [eː] than for [iː], [i]. In the dorsal-pharyngeal region, measured with ultrasound, [iː] was affected the most while [eː] was affected the least. This difference, which was significant only for ZZ, was presumably due to the fact that the two methodologies provide information about different tongue regions, and due to the tongue's flexibility for partially independent movements in these different regions.

4.2. Monosyllabic words

4.2.1. Effect of harmonic type: EMMA

The set of monosyllabic stimuli was comprised of monosyllables with transparent vowels that trigger either front or back suffixes. As described in Section 3.2, the transparent vowels in this set of stimuli are de-contextualized and the influence of adjacent vowels on the production of transparent vowels was controlled: the transparent vowel was the only vowel in the target word, and the vowels of the frame sentence were constant.

One-way anova tests showed that harmonic type significantly affected the position of the receivers placed on the tongue. This was the case for one receiver for subject ZZ ($F(1,124) = 4.005$, $p = .048$ for TB2) and all three receivers for subject BU ($F(1,116) = 6.940$, $p = .010$ for TD; $F(1,116) = 11.403$, $p < .001$ for TB2; $F(1,116) = 7.453$, $p = .007$ for TB1). The monosyllabic stimuli for the pilot subject CK contained only 12 tokens (4 repetitions of three lexical pairs) in each harmonic type (front vs. back). In 9 out of 12 pairs, the transparent vowel in the stems selecting back suffixes was more retracted than in the stems selecting front suffixes for the TD receiver.

Parallel to Table 1, Table 8 shows the size and the direction of the effect that harmonic type had on the horizontal position of the vowels. The values in the columns labeled F and B are the means of the horizontal maxima of the receivers during the transparent vowels in the words of the front and back harmonic type, respectively, and they are shown in millimeters. The values in the MD column represent the difference between the mean values for the position of the receivers in the two harmonic types. The absolute value of MD thus corresponds to the size of the effect, and its sign shows the direction of the effect.

All MD values except one (CK's TB1 receiver) were positive. Thus, the degree of advancement in the front harmonic type was greater than in the back harmonic type. Moreover, this effect of harmonic type was

Table 8
Direction and size of the effect of harmonic type

Rec.	ZZ			BU			CK		
	F	B	MD	F	B	MD	F	B	MD
TD	−46.67	−47.03	.36	−42.08	−42.61	.53*	−22.25	−22.94	.69
TB2	−36.15	−36.93	.78*	−29.54	−30.38	.84*			
TB1	−20.35	−20.73	.38	−20.07	−20.6	.53*	−20.00	−19.78	−.22

Mean difference (MD) = Front (F)–Back (B).

Table 9
Mean difference (MD) in mm between the tongue shapes from the front and back harmonic types

Block	$\mathrm{MD} = D_{\mathrm{Front}} - D_{\mathrm{Back}}$				
	Line-1	Line-2	Line-3	Line-4	Line-5
1	.32	−.11	.06	.06	−.15
2	.63	.86	.68	.39	−.12

significant for four out of six dependent variables: all three receivers for subject BU and one receiver (TB2) for subject ZZ.

Overall, then, EMMA data showed that transparent vowels in monosyllables of the back harmonic type were more retracted than phonemically identical transparent vowels in monosyllables of the front harmonic type. Because monosyllabic stimuli were presented in isolation (no suffixes), the observed sub-phonemic differences cannot be attributed to contextual coarticulation. These differences must be part of the speakers' knowledge of these stems.

4.2.2. *Effect of harmonic type: ultrasound*

The area measured with the ultrasound data from ZZ's monosyllabic words supported the EMMA result: harmonic type had a significant effect on the global shape of the tongue. A two-way anova was conducted with factors H-TYPE and BLOCK. The main effect of harmonic type was significant, $F(1{,}444) = 8.848$, $p = .003$, and BLOCK was also significant, $F(1{,}444) = 7.604$, $p < .006$. The interaction H-TYPE*BLOCK was not significant, $F(1{,}444) = 1.145$, n.s. For both blocks separately as well as combined, the area between the curves from different harmonic type was consistently greater than for curves from the same harmonic type.

Table 9 shows the effect of harmonic type measured in the reference system of five fixed lines. When all data were pooled, harmonic type did not have a significant effect on the position of the tongue. All the differences in Block 1 were within measurement error. Similarly to tri-syllabic words, the effect of harmonic type in Block 2 was greater and more consistent than in Block 1. Four out of five measures in Block 2 showed positive MD values, which signals that transparent vowels in back-selecting stems were more retracted than in front-selecting stems. However, this effect was significant only at $p = .1$, $F(1{,}318) = 2.915$, $p = .089$.

Hence, despite the fact that the significance of effect of harmonic type was not conclusive in the ultrasound data, the direction of the effect corroborated other findings: on average, transparent vowels in words selecting back suffixes were more retracted than transparent vowels in words selecting front suffixes.

4.3. *Trisyllabic vs. monosyllabic words*

The results presented in the previous two sections established that the transparent vowels in the trisyllabic and monosyllabic words were affected by harmonic type in a similar fashion. However, the data also showed differences with respect to the strength of the influence that harmonic type exerted on them. Table 10 summarizes these differences in the EMMA data.

Table 10
The amount of retraction in trisyllabic and monosyllabic words in the EMMA data

Subject	Receiver	MD	
		3-syll.	1-syll.
ZZ	TD	.95	.36
	TB2	1.39	.79
	TB1	1.32	.37
BU	TD	.39	.51
	TB2	.59	.80
	TB1	.39	.54

It can be seen that the effect of harmonic type for subject ZZ was smaller for the monosyllabic words (yet still significant for the TB2 receiver) than for the trisyllabic words. The ultrasound data for this subject corroborated this observation. The opposite effect can be seen in the EMMA data for subject BU. In this subject's dataset, harmonic type affected the transparent vowels in the monosyllabic words to a slightly greater degree than the same vowels in the trisyllabic words. Possible reasons for the differences seen here will be discussed in Section 5.1.

5. Summary and discussion

5.1. Trisyllabic and monosyllabic words

The production of Hungarian transparent vowels {[iː], [i], [eː]} was investigated with the use of magnetometry and ultrasound using two different sets of stimuli. The first stimuli set consisted of trisyllabic words where a transparent vowel was flanked by either back or front vowels (e.g. *bili̲-vel* vs. *buli̲-val*). The major finding was that transparent vowels in the front harmony context were more advanced than in the back harmony context. This effect was robust and highly significant for all three subjects and all quantification methods.

The second stimuli set consisted of monosyllables where the same transparent vowel triggers either front suffixes (e.g. *hír-nek*, *éj-nek*) or back suffixes (e.g. *ír-nak*, *héj-nak*). Harmonic type affected the tongue position so that transparent vowels that trigger front suffixes were more advanced than (phonemically identical) transparent vowels that trigger back suffixes. This effect was significant in at least one quantification method for each subject. Hence, transparent vowels in monosyllabic words behave comparably with transparent vowels in trisyllabic words.

Although the trisyllabic and monosyllabic words showed a similar effect of harmonic type, the data also showed differences in the strength of the influence that harmonic type exerts on them. These differences were summarized in Table 10 and showed that in ZZ's dataset the mean effect of harmonic type was smaller for the monosyllabic words than for the trisyllabic words whereas in BU's dataset the mean effect was greater in the monosyllables than in the trisyllables.

The comparison in Table 10, however, should be considered with caution. First, the monosyllabic stimuli differed from the trisyllabic ones prosodically. Hungarian words are stressed on the initial syllable and so the transparent vowels in the monosyllabic words receive word stress whereas they are unstressed in the trisyllabic words.

The second consideration is that the trisyllabic stimuli were balanced in terms of the type of the transparent vowel, but this was not the case for the monosyllabic stimuli. Recall that out of 22 trisyllabic words, 7 contained [iː], 8 contained [i], and 8 contained [eː]. In contrast, out of 8 monosyllabic words, 5 contained [iː], only 1 contained [iː], and 2 contained [eː]. Hence, monosyllables with long [iː] were well represented in the data whereas monosyllables with [iː], [eː] were under-represented (for reasons discussed in Section 3.2). The comparison of trisyllabic and monosyllabic words with [iː] in ZZ's data reveals that harmonic type has a greater effect on the vowel [iː] in the monosyllabic words than in the trisyllabic ones. For all three receivers, the difference between the positions of the tongue in the two harmonic types was greater in the monosyllabic words (.76 vs. .56 for TD, 1.23 vs. .59 for TB2, and 1.15 vs. .31 for TB1). Hence, two generalizations can be observed in ZZ's data. Across all stimuli, the effect of harmonic type was greater in the trisyllabic words than in the monosyllabic ones. However, when we focus on the vowel that is best represented in both the trisyllabic and monosyllabic words, the effect of harmonic type was greater in the monosyllabic than in the trisyllabic ones.

In BU's data, where the type of vowel was not significant, the imbalance in the monosyllabic stimuli did not affect the overall MD values so much. For example, the effect of harmonic type for the best represented [iː] was similar in the monosyllabic and trisyllabic stimuli (.62 vs. .51 for TD, 1.02 vs. .80 for TB2, .55 vs. .54 for TB1).

These considerations, however, question only the validity of comparing the size of the main effect of harmonic type between the monosyllabic and trisyllabic words in this data set. They do not undermine the significance of the harmonic type in both categories of stems.

The results presented here show that behind the phonological arbitrariness of transparency lies a phonetic coherence. Phonologically, transparent vowels are front vowels that are sometimes followed by front and sometimes by back suffixes. However, a finer look reveals an underlying phonetic coherence in two respects. First, transparent vowels in back harmony contexts are retracted versions of their phonemically identical vowels in front harmony contexts (e.g. *buli̠-val* vs. *bili̠-vel*). Second, transparent vowels in monosyllabic words selecting back suffixes are retracted versions of phonemically identical vowels in stems that select front suffixes (e.g. *éj* taking front suffixes compared to *héj* taking back suffixes). Overall, the coherence emerges when sub-phonemic properties of transparent vowels are examined and linked to the phonological form of the following suffix.

5.2. Transparent vowels and harmonic type: incomplete neutralization

The experimental findings of this study show that the Hungarian vowels {[iː], [i], [eː]} have two variants depending on the harmonic type in which they appear: a more advanced variant in the front harmony type words and a less advanced one in the back harmony type words. Yet, the phonological literature and impressionistic intuitions of Hungarian native speakers suggest that the two variants are non-contrastive.[18] The observed differences in the production of Hungarian transparent vowels in the two harmonic types thus bear characteristics of incomplete neutralization and near merger.

In incomplete neutralization, a categorical contrast between two sounds is neutralized phonologically in certain environments but quantitative traces of that difference may persist at the phonetic level (Charles-Luce, 1993, 1997; Dinnsen, 1985; Fougeron & Steriade, 1997; Piroth & Janker, 2004; Port & O'Dell, 1985; Slowiaczek & Dinnsen, 1985; Warner et al., 2004; see also the discussion in Port, 1996; Manaster-Ramer, 1996). A well-known example is voicing neutralization of syllable-final obstruents in German, Polish, or Catalan. Although underlyingly voiced and voiceless obstruents are considered and transcribed as voiceless syllable-finally, speakers produce these two categories with slight but systematic phonetic differences. Some studies have shown that listeners are able to reconstruct the underlying distinctions in voicing based on surface data (Ernestus & Baayen, 2006; Port & Crawford, 1989).

In near mergers, subjects produce systematic articulatory differences between two sounds which they do not consistently perceive. Much of the evidence on near mergers comes from sociolinguistic research. For example, Labov et al. (1993) report the results of Janson and Schulman (1983) who investigated the contrast between the vowels [e] and [ɛ] in two Swedish dialects. In a production experiment, Stockholm speakers did not produce any consistent differences between the two vowels, whereas Lycksele speakers did. In a subsequent perception experiment, subjects listened to the pronunciations of the vowel tokens from the production experiment. When Lycksele subjects listen to the contrastively produced vowels extracted from their own

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[18] But see Labov et al. (1993, p. 37) on questioning the reliability of native speakers' intuitions in the perception of phonological categories.

speech, they did not reliably perceive this contrast. Hence, a contrast between the two vowels was not present in perception despite its presence in production.[19]

The behavior of transparent vowels described in this paper is thus similar to other cases of incomplete neutralization and near merger in that phonemically identical instances of non-low front vowels show systematic articulatory variants. The diachronic evidence available to us reasonably suggests that the sound change leading to transparency originated from the loss of contrast or merger between front and back unround vowels in prosodically weak contexts and was completed in all contexts and throughout the language area by the 11th century (Kálmán, 1972).[20] As in other cases of near mergers, our data show that there remains a reliably discernible distinction in articulation that is reminiscent of the original contrast.

However, there is also a difference between our Hungarian data and previous cases of incomplete neutralization and near merger. The locus of this difference is in the relation between the phonological rules underlying the phenomenon of interest and the rest of the sound system of a particular language. The cases of incomplete neutralization and near merger documented so far typically involve phonological rules that apply without exceptions once their environment is satisfied, and they are usually allophonic because they affect non-contrastive features of sounds (in the environment of their application). Moreover, these rules typically do not interact with other phonological processes and show the influences of style, rate of speech, or orthographic conventions of a particular language. In terms of the typology of phonological rules proposed by Lexical Phonology, rules that share these characteristics are known as post-lexical rules (Kiparsky, 1982). The Hungarian data differ from these cases of incomplete neutralization and near merger in that in Hungarian the observed sub-phonemic distinctions are linked to a prototypical lexical rule, giving rise to the productive morpho-phonological alternation of vowel harmony. Vowel harmony is a prime example of a phonological regularity that can operate independently of style or rate of speech and orthographic conventions. It also exhibits exceptional behavior, involves non-adjacent sounds, and affects contrastive features of sounds.

In sum, the systematic sub-phonemic distinctions uncovered in our experiments are similar to distinctions found in incomplete neutralizations or near mergers. In both cases, subjects show quantitative sub-phonemic differences in production. But unlike in cases of incomplete neutralization or near merger, the sub-phonemic distinctions in transparent vowels correlate with a prototypical phonological alternation of the suffix forms in the vowel harmony system of Hungarian.

5.3. *Harmonic type and coarticulation*

Combining the results from the two Hungarian stimuli sets, harmonic type affects a transparent vowel both when it is adjacent to other vowels in a word as well as when it is the only vowel in a word. This result does not support the assumption that the phonetic differences between phonemically identical transparent vowels in the front and back harmonic type words are directly related to phonetic coarticulation from adjacent vowels (see Fónagy, 1966 for Hungarian and Gordon, 1999; Välimaa-Blum, 1999 for Finnish). For example, tongue body retraction and concomitant F_2 lowering of [i] in *buli-val* [bulivɔl] 'party-Instrumental' may be hypothesized to arise from phonetic coarticulation with the surrounding back vowels. In monosyllabic stems that take back suffixes such as *híd* [ɦiːd] and *cél* [t͡seːl], however, there were no vowels adjacent to the transparent vowels and the effect of harmonic type was still observed: the [iː] in stems like *híd* was more retracted than the [iː] in stems like *íz*, when these stems were produced in their bare form (no suffixes). Therefore, purely mechanical coarticulation operating within isolated lexical items does not sufficiently explain the articulatory differences found in our data.

It is conceivable, however, that these differences might be accounted for by a model of lexical storage where representations encode phonetic details beyond the scope of standard segmental and featural representations. One such class of models are exemplar-based models of lexical storage (Johnson, 1997; Kirchner, 1999; Pierrehumbert, 2001). Within this class of models and abstracting away from details of representation yet to be worked out, variability in the production of a category is achieved by averaging and/or randomization over a set of memorized exemplars of the category, generating a so-called 'echo' of the category. The key is that

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[19] Some Lycksele subjects perceived the contrast with minimal error whereas others performed at chance. As Labov et al. note, near mergers are characterized by heterogeneity in the behavior of the subjects. See also discussion in Pierrehumbert (2002).

[20] To the best of our knowledge, this prosodically conditioned reduction is not present in Hungarian synchronically.

exemplars are representations that admit quantitative or sub-categorical phonetic details. Therefore they may reflect properties of the phonetic context in which they are embedded. Based on this crucial property, an exemplar-based model could account for the observed differences in the Hungarian monosyllabic stems in the following way. Given that Hungarian stems can occur with various suffixes, a back-selecting stem such as *híd* [ɦiːd] ‘bridge’ would be produced in various contexts as *híd-nak* [ɦiːdnɔk], *híd-hoz* [ɦiːdɦoz], *híd-nál* [ɦiːdnɑːl], …, and *híd-*∅ [ɦiːd]. In contrast, a front-selecting stem such as *víz* [viːz] ‘water’ would be produced as *víz-nek* [viːznɛk], *víz-hez* [viːzɦɛz], *víz-nél* [viːzneːl], …, and *víz-*∅ [viːz]. The exemplars of [iː] associated with *híd* would then be on average more retracted (with lowered F_2) than the exemplars of [iː] in *víz* because they are affected by coarticulation from the back suffix vowels. The bias for more retracted exemplars associated with *híd* mirrors the input data and can be transformed into a corresponding production difference in terms of tongue body retraction, assuming an appropriately worked out model of the perception-production loop (see Kirchner, 1999 for a proposal). Crucially, even productions of bare (unsuffixed) *híd* and *víz* would show differences in retraction. This is because the value of F_2 for the production of [iː] in bare *híd* would be supplied by the echo from the cloud of exemplars associated with *híd.* Because the ‘híd-cloud’ contains exemplars where [iː] is coarticulated with the following back vowel and the ‘víz-cloud’ does not, [iː] in *híd* is predicted to be more retracted than [iː] in *víz.* According to this model, then, Hungarian speakers can store and reproduce fine phonetic differences among transparent vowels, and these differences can be argued to be derivable from coarticulatory influences of the context in which these vowels appear.

While it is true that an exemplar model may in principle be able to encode and derive the differences observed in our data, it is not, on its own, sufficient for understanding the nature of transparency. For example, such a model would not provide answers to questions such as why [iː] is transparent but [y] is consistently opaque in palatal harmony systems, or why [e] is cross-linguistically more opaque than [iː] (Anderson, 1980a).[21] In fact, given an appropriately constructed input set of training data, exemplar-based models could be trained so as to reproduce unattested patterns of palatal vowel harmony, e.g. a system where [i] is opaque and [y] is transparent, or a system where [eː] is more transparent than [i]. We thus turn to address the central issue of the nature of transparency in the next section.

5.4. Phonetic basis of transparency

At the outset of this paper we discussed V-to-V coarticulation as a plausible phonetic basis for vowel harmony that did not seem consistent with the phonetic and phonological properties of transparent vowels. Here we return to this issue in light of the presented articulatory results demonstrating that the non-low front vowels in Hungarian are articulatorily permeable in the front–back dimension. Combining these results with evidence on the perceptual stability of non-low front vowels enables us to formulate a hypothesis grounding transparency in characteristics of the relation between articulation and acoustics of these vowels. Specifically, the hypothesis is that transparent vowels in palatal vowel harmony are those vowels that can be articulatorily retracted to a certain degree while still maintaining their front perceptual quality. This hypothesis makes specific predictions about correlations between the phonetics and the phonological patterning of different vowels that we discuss in this section.

A core idea in formulating our hypothesis is that the relation between acoustic and articulatory dimensions of phonetic form displays discontinuous characteristics (Stevens, 1972, 1989). In ‘stable’ regions of an abstract

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[21] Additionally, a model of our data that is based on coarticulation from adjacent vowels, as is the case for an exemplar model, should also address two potentially problematic observations. First, in trisyllabic words, phonetic coarticulation is expected to impart a stronger effect on short than on long vowels. This is because long vowels have more time to achieve their target and are thus less prone to contextual coarticulatory influences than their short counterparts. Hungarian has a phonemic length distinction, with phonemically long vowels being 1.5–2 times longer phonetically than the short vowels (Magdics, 1969, p. 16), which was also verified in our data (subject BU). In the transparent vowels used in our experiments, there were two long vowels, [iː] and [eː], and one short vowel [i]. In the EMMA data, [eː] was affected by harmonic type the most. In the ultrasound data, it was the other long vowel [iː] that was affected the most. Therefore, long vowels were affected by harmonic type more than short vowels. Second, as discussed in the previous section, in some datasets the effect of harmonic type was greater in the monosyllabic than in the trisyllabic words. One would expect that the effects of remnant (exemplar-based) coarticulation and real-time surface coarticulation in tri-syllabic words would be additive. That is, transparent vowels in trisyllabic words would be expected to consistently show a greater effect of harmonic type than monosyllabic words.

articulatory-acoustic space, change along an articulatory dimension does not result in significant change in acoustics. In 'unstable' regions, however, comparable articulatory change can cause significant difference in acoustics. Stevens argued that Universal Grammar utilizes the presence of such discontinuities in the dual form of phonetic substance to encode contrasts in phonological systems. Moreover, the presence of such regions, according to Stevens, explains why the abundance of coarticulation in natural speech does not hinder perception.

One group of sounds with documented discontinuities in the relation between articulation and acoustics are the non-low front unround vowels. Calculations using both simple tubes (Stevens, 1989) as well as natural human vocal tract profiles (Wood, 1979) show that the acoustic outputs for non-low front vowels are insensitive to a limited amount of variation in the horizontal position of the tongue body. For example, the vowel [iː] may be articulatorily retracted to some degree without losing its perceptual identity.

The central result is illustrated in Fig. 5. The S-like curve divides the abstract phonetic space into the stable Regions I and III and the unstable Region II. The horizontal coordinate of the ball sitting on the curve represents the locus of a palatal constriction formed by the tongue body articulator. The black ball corresponds to a tongue body position with the palatal constriction of a prototypically front vowel. The slightly retracted tongue body position illustrated with the gray ball falls in the stable region of perceptual stability and a vowel with this constriction location is still considered a front vowel.

The foundational results of Stevens and Wood above are not specific to a particular language. Rather, they characterize properties of the articulatory–acoustic relations in a language-independent set of vowels, the non-low front unround vowels. These are precisely the transparent vowels of palatal vowel harmony systems like Hungarian and Finnish. In this sense, the articulatory–acoustic relations reviewed above provide a plausible phonetic basis for transparency: transparent vowels in palatal vowel harmony are those vowels that can be articulatorily retracted to a certain degree but maintain their perceptual quality of being front. Other research provides additional sources of evidence for the acoustic stability of [i] and [e], manifested as resistance to coarticulation from adjacent vowels (Beddor et al., 2001; Recasens, 1999). The present study adds articulatory support to that evidence from transparent vowels, that is, phonemically identical vowels showing systematic articulatory differences correlating with the phonological form of the following suffix.

To review, then, the main result of our experiments was that the harmonic type of a stem is realized as a sub-phonemic difference in the tongue body position of transparent vowels. Transparent vowels in the front-selecting stems are produced with the tongue body more advanced than the phonemically identical vowels that occur in back-selecting stems. Importantly, the non-linearity in the articulatory–acoustic relations in these vowels ensures that these articulatory differences cause minimal differences in their acoustic output. Hence, in impressionistic transcriptions these vowels are transcribed with a phonemically invariant category even though there are systematic articulatory differences.

Two consequences follow from the hypothesis grounding transparency in articulatory–acoustic relations. The first is that the hypothesis allows one to bring order and coherence to a previously seemingly unrelated set of generalizations found in language-particular and cross-linguistic data. Second, the hypothesis guides future research in Hungarian and other languages by making specific predictions about data that can be obtained. We discuss each of these points in turn.

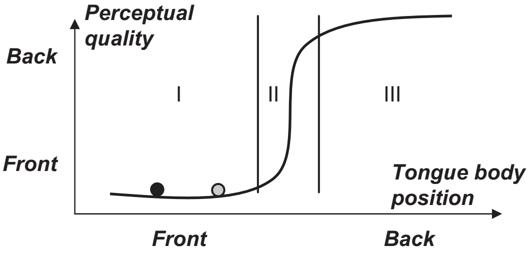

Fig. 5. Non-linearity in front non-low unround vowels. Tongue body retraction is shown as the difference between the x-coordinates of the two balls, while the minimal perceptual effect of this retraction is shown on the y-axis.

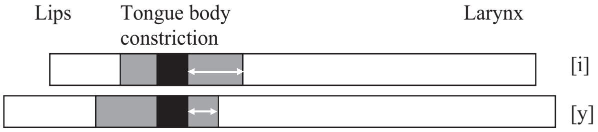

Fig. 6. Illustration of the quantal differences between [i] and [y].

One important generalization in the phonological patterning of transparency concerns front round vowels. Phonologically, front round vowels do not behave transparently in palatal vowel harmony systems. In Hungarian, for example, front round vowels in stem-final position are always followed by front suffixes irrespective of the quality of the preceding vowels (*parfüm-nek* [pɔrfymnɛk], **parfüm-nak* [pɔrfymnɔk] 'perfume-Dative', *tök-nek* [tøknɛk], **tök-nak* [tøknɔk] 'pumpkin-Dative'). In contrast, front unround vowels can be followed by front or back suffixes. Both Stevens (1989) and Wood (1986) showed that rounding in front vowels significantly affects their quantal properties. In front round vowels the degree of perceptually tolerated tongue body retraction is more limited than for unround vowels. The reason for this is the difference in the effective position of the constriction relative to the length of the vocal tract. Rounding increases the length of the vocal tract. This effectively advances the stable region in which horizontal articulatory perturbations have minimal acoustic effects. Fig. 6 illustrates this idea. The long white box represents the vocal tract, the gray box represents the stable area of acoustic insensitivity to articulatory variation, and the black box represents the canonical location of the palatal constriction. The relations between [i] and [y] illustrated in Fig. 6 are based on the previously reported data. Specifically, the elongation of the vocal tract for [y] as compared to [i] (white boxes) by rounding is well documented and lowering the larynx as a compensation for rounding has been documented by Wood (1986). The similarity in the horizontal position of the palatal constrictions (the black boxes) has also been previously described (e.g. Wood, 1986, p. 393) and was confirmed in our Hungarian data by comparing the ultrasound images from the non-sense words [bib] and [byb]. The relative fronting of the region with insensitivity to articulatory perturbation (gray box) was demonstrated in nomograms of formant resonances in Stevens (1989, p. 17) and Wood (1986, p. 396). As far as we can tell from these nomograms, the size of this region does not significantly change by rounding, so the gray boxes in the figure have the same size.

Comparing now the two panels, the tongue body constriction for [i] (top panel) is flexible in that it can be retracted to some degree while still remaining within the stable region. This retraction is depicted with the white arrow. For [y], bottom panel, the extension of the vocal tract due to lip rounding advances the stable region despite compensation at the larynx.[22] Consequently, the potential degree of tongue body retraction for [y] is minimal. Due to these factors, the horizontal tongue body position for [y] is hypothesized to be more constrained than that of [i] in the context of adjacent back vowels.

As mentioned, front unround vowels behave transparently while round vowels behave opaquely in Hungarian and other palatal vowel harmony systems (e.g. *papír-nak* [pɔpiːrnɔk] 'paper-Dative' vs. *parfüm-nek* [pɔrfymnɛk] 'perfume-Dative'). Hence, the binary (phonological) choice in suffix form correlates with differences in the quantal characteristics of stem-final vowels: front vowels for which some articulatory retraction is perceptually tolerated are followed by either front or back suffixes whereas front vowels for which comparable retraction is not tolerated are followed by front suffixes only.[23]

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[22] Wood concluded that this depression is essential to compensate for the lip rounding: the area of F_2 insensitivity to articulatory perturbation for round vowels thus remains in the pre-palatal region. Crucially, however, this area is still more anterior than for unround vowels (Wood, 1986, p. 400).

[23] Additional support for differences in the perceptual consequences of articulatory retraction between round and unround front vowels comes from observations on Finnish palatal harmony. Finish has a similar vowel harmony system to that of Hungarian in which [i] and [e] are transparent but their round counterparts [y] and [ø] are not transparent. Campbel (1980) reported that front round vowels in a back harmonic context are perceived as back vowels, while Wiik (1995) and Välimaa-Blum (1999) reported intermediate values of acoustic backness. For example, Wiik assigns a central quality [ʉ] to the high front round [y] in a back harmony context. A plausible explanation of these observations is that front round vowels in a back harmonic context are retracted to a degree that imparts a non-front perceptual quality on them, for reasons related to the advancement of their quantal region described in Fig. 6.

Another generalization concerns the relation between vowel height and transparency. In Hungarian, stems in which a back vowel is followed by [ɛ] are commonly described as 'vacillating' because they allow both front and back suffixes (Vago, 1980). Hence, stems such as *hotel* vacillate: *hotel-nak/nek* [hotɛlnɛk, hotɛlnɔk] 'hotel-Dative'; but stems such as *papír* do not vacillate: *papír-nak* [pɔpiːrnɔk], **papír-nek* [pɔpiːrnɛk] 'paper-Dative'. Thus the generalization is that the lower and more retracted [ɛ] is phonologically less transparent than the higher and more front [i]. In fact, a similar generalization is true for Finnish and other palatal vowel harmony systems (Anderson, 1980a). Therefore, there is a correlation between height and transparency, and the opposite generalization that lower vowels are more transparent than higher vowels is not attested.

Phonetically, the production of front low vowels is less flexible in the horizontal dimension of the tongue body constriction location than the production of high vowels (e.g. Beckman et al., 1995, p. 480-1; Wood, 1979). This is due to the fact that the constriction required for low vowels is less 'consonant-like' than that required for high vowels. Ultrasound comparison of [i] and [ɛ] in our data showed considerable difference between [i] and [ɛ] in the vertical position of the tongue body, supporting the characterization of [ɛ] as a mid-low or even low front vowel. Due to this decrease in articulatory flexibility for [ɛ], the difference between [i] and [ɛ] is similar to the previously discussed difference between [i] and [y] in that potential articulatory retraction of [ɛ] is more limited than potential retraction of [i]. In other words phonologically transparent [i] is perceptually more stable and articulatorily more permeable, i.e. more 'quantal', than less transparent [ɛ].

The final generalization concerns the relationship between suffix choice and the number of transparent vowels in disharmonic stems: stems where a back vowel is followed by two transparent vowels (BTT stems) are more likely to vacillate or take front suffixes than BT stems. For example, *mam-i* [mɔmi] and *mam-csi* [mɔmt͡ʃi] (both forms mean 'mom-Diminutive') select back suffixes: *mami-nak* [mɔminɔk], *mamcsi-nak* [mɔmt͡ʃinɔk] 'mom-Diminutive-Dative'. However, when the two diminutive suffixes are combined in *mamicsi*, both front and back suffixes are acceptable: *mamicsi-nak/nek* [mɔmit͡ʃinɔk, mɔmit͡ʃinɛk] 'mom-Dative' (Farkas & Beddor, 1987; Hayes & Londe, 2006; Kaun, 1995; Ringen & Kontra, 1989). This generalization is difficult to express in traditional models where transparent vowels are assumed to be invisible in vowel harmony. The problem is that if one excludes transparent vowels from harmony, then their number should not affect suffix choice. In other words, transparency is not a categorical property of vowels but it is determined contextually. The same vowel can be transparent in one context (e.g. *mamcs**i**-nak*) but opaque in another (e.g. *mamics**i**-nek*).

Under the assumption that all vowels, including transparent ones, participate in harmony, the horizontal advancement of stem-final vowels in BT and BTT stems is predicted to be different. Thus, the stem-final /i/ in *mami* should be less advanced than the stem-final /i/ in *mamicsi* because the intervening front vowel in the BTT stem eliminates partially the coarticulatory influence of the initial back vowel. Phonologically, *mami* selects only back suffixes whereas *mamicsi* can also select front suffixes. Hence, the assumed relationship between the phonetic advancement of the tongue body in stem-final vowels and the choice of the following suffix vowel in *mami* and *mamicsi* is consistent with the other observations discussed in this section: a stem-final front vowel that is more retracted is more likely to be followed by back suffixes than a phonemically identical vowel that is less retracted.

To summarize, we proposed that a plausible phonetic basis for transparency in palatal vowel harmony can be formulated by reference to the link between articulation and acoustics of transparent vowels. The foundational theoretical notion is that of non-linearity in the relation between articulation and acoustics. This notion allows one to make sense of both language-specific and cross-linguistic phonological patterns and the observed phonetic regularities in our experiments. For a formal model incorporating these ideas, see Gafos and Benus (2006) and Benus and Gafos (2005). The model is based on the quantal theory notions presented in this section. Its crucial formal property is that it allows us to relate the continuous phonetic distinctions in tongue body retraction of transparent vowels to the binary alternation in the phonological form of the suffix (front vs. back) using the mathematics of non-linear dynamics.

Moreover, the hypothesis outlined in this section provides testable predictions for further experimental work in Hungarian and other languages. These predictions concern links between the phonological behavior of transparent/opaque vowels, on the one hand, and the relative values of articulatory retraction and their acoustic and perceptual consequences, on the other hand. For example, we plan to test the predicted relative differences in retraction degrees of stem-final vowels in BT vs. BTT stems like *mami* [mɔmi] vs. *mamicsi* [mɔmit͡ʃi], in *papír* [pɔpiːr] vs. *parfüm* [pɔrfym], and in *papír* [pɔpiːr] vs. *hotel* [hotɛl] in a future study.

Connected to this line of research are perception experiments, as suggested by our reviewers, testing the ability of Hungarian speakers to differentiate variably retracted transparent vowels.

6. Conclusion

The experiments reported in this study provide, for the first time, a systematic articulatory description of transparent vowels in a language with vowel harmony. The main result was that the harmonic type of a stem is realized as a sub-phonemic difference in the tongue body position of transparent vowels. Transparent vowels in the front-selecting stems are produced with the tongue body more advanced than the phonemically identical vowels that occur in back-selecting stems. Hence, transparent vowels do participate in vowel harmony at the phonetic level.

A striking property of the data was that even the vowels in isolated monosyllabic stems showed differences in articulation that correlate with their suffix choices. Thus, transparent vowels in monosyllabic stems selecting back suffixes were more retracted than phonemically identical vowels in monosyllabic stems selecting front suffixes. Crucially, these differences emerge from stems elicited in their un-suffixed forms.

Finally, we proposed that a plausible phonetic basis for transparency can be found in characteristics of the relation between articulation and acoustics of transparent vowels. The proposed phonetic basis allows one to relate a previously seemingly unrelated set of observations about the effect of rounding, height, and number of transparent vowels in vowel harmony. The proposed phonetic basis also makes specific predictions about data that can be obtained in future experiments. More broadly, the proposal is that the phonological behavior of transparent vowels can be better understood when the phonological patterning of these vowels is studied together with their articulatory and acoustic characteristics.

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Appendix A

A.1. List of stimuli for subjects ZZ and BU

Back	Gloss	Front	Gloss	Suffix
Trisyllabic words				
/**í**/				
zafír-ban	sapphire	zefír-ben	zephyr	Iness.
zafír-ból	sapphire	zefír-ből	zephyr	Elat.
zúdít-ott	to hail	szédít-ett	to beguile	3rd Sg. past indef.
tompít-ó	attenuative	tömít-ő	obturating	adject. suff.
normatív-nél	normative	primitív-nál	primitive	Adess.
passzív-hoz	passive	esszív-hez	essive	Allat.
Szólít-od	to address	bővít-ed	to let out	2nd Sg. def.
/**i**/				
bácsi-ban	uncle	bécsi-ben	of Vienna	Iness.
buli-val	party	bili-vel	pot	Instr.
kocsi-tól	carriage	öcsi-től	buster	Abl.
polip-om	polyp	Filip-em	Filip	1st Sg poss.

szolid-nak	solid	rövid-nek	short	Dat.
bólint-ott	to nod	érint-ett	to touch	3rd Sg. past indef.
Tomi-hoz	Tom.Dim.	Imi-hez	Imre.Dim.	Allat.
Lutri-hoz	lottery	csitri-hez	flapper	Allat.
/**é**/				
szatén-ban	satin	kretén-ben	cretin	Iness.
tányér-nál	plate	tenyér-nél	palm	Adess.
málé-hoz	spoon	filé-hez	fillet	Allat.
sasszé-val	shuffle	esszé-vel	essay	Instr.
málés-an	stupid	békés-en	peaceful	adject. suff.
ganéz-ott	be composetd	intéz-ett	manage	3rd Sg. past indef.
kadét-tól	cadet	bidé-től	bidet	Abl.

Back		Front	
Monosyllabic words			
vív	fence	ív	bow
híd	bridge	íz	flavor
ír	write	hír	rumor
víg	cheerful	míg	while
síp	whistle	cím	address
nyit	open	hisz	believe
cél	aim	szél	wind
héj	crust	éj	night

Frame sentence:
Azt mondom, hogy ____ *és elismétlem azt*, *hogy* ____ *mégegyszer*. ‘I say ____ and I repeat ____ once again.’

Appendix B

B.1. List of stimuli for subject CK (pilot)

Trisyllabic & disyllabic words

Back	Gloss	Front	Gloss	Suffix
í				
zafír-ban	sapphire	zefír-ben	zephyr	Iness.
zafír-tól	sapphire	zefír-től	zephyr	Abl.
zafír-hoz	sapphire	zefír-hez	zephyr	Allat.
aktív-ál	Active	beszív-el	to draw	Adj.
naív-ul	Naïve	beív-el	to lob	Adj.
masszív-val	massive	műszív-val	art. heart	Inst.
masszív-hoz	massive	műszív-hez	art. heart	Allat.
masszív-ba	massive	műszív-be	art. heart	Illat.
passzív-val	Passive	kőszív-val	heart of adamant	Inst.
passzív-hoz	Passive	kőszív-hez	heart of adamant	Allat.
zúdít-ott	to hail	szédít-ett	to beguile	3rd Sg. past i ind.
jobbít-om	to ammend	kisebbít-em	to lessen	1st Sg. poss.
kábít-om	to daze	repít-em	to send	1st Sg. poss.
i				
náci-val	Nazi	nőci-vel	bimbo	Inst.
náci-ban	Nazi	nőci-ben	bimbo	Iness.

náci-hoz	Nazi	nőci-hez	bimbo	Allat.
bácsi-val	Uncle	bécsi-vel	of Vienna	Inst.
bácsi-ban	Uncle	bécsi-ben	of Vienna	Iness.
bácsi-hoz	Uncle	bécsi-hez	of Vienna	Allat.
buli-val	Party	telivér	full-blood(ed)	Inst.
buli-ban	Party	belibeg	to breaze in	Iness.
cumi-ban	Title	semmibe	to ignore	Iness.
kocsi-tól	Coach	kicsi-től	small	Abl.
lutri-val	Lottery	csitri-vel	flapper	Inst.
lutri-hoz	Lottery	csitri-hez	flapper	Allat.
lutri-ba	Lottery	csitri-be	flapper	Illat.
mázli-val	Fluke	müzli-vel	muesli	Inst.
nyuszi-tól	Bunny	tenyésztidő	breeding season	Nominal
polip-on	Polyp	zsilip-en	sluice	Superess.
polip-om	Polyp	Fillip-em	name	1st Sg poss.
cuclitam	pacifier	filiszter	philistine	Root
kap-ni	to get	köp-ni	to gob	Inf.
lop-ni	to pinch	lép-ni	to step	Inf.

é

acél-nak	Steel	beszél-nek	to address	Dat.
affér-ban	Affair	térbeli	spatial	Iness.
bode-tól	Hut	bidet-től	bidet	Abl.
kávé-val	Coffee	végé-vel	end	Inst.
soltész-ból	Name	tengerész-ből	mariner	Elat.
tányér-hoz	Plate	tenyér-hez	palm	Allat.
málé-val	Spoon	felé-vi	terminal	Inst.
málé-hoz	Spoon	léhű-tő	loafer	Allat.
sasszé-val	shuffle	esszé-vel	essay	Inst.
sasszé-ból	shuffle	esszé-ből	essay	Elat.
sasszé-hoz	shuffle	Esszé-hez	essay	Alat.
csálé-val	croocked	meggylé-vel	sour cherry juice	Inst.
csálé-ban	croocked	meggylé-ben	sour cherry juice	Iness.
csálé-hoz	croocked	meggylé-hez	sour cherry juice	Allat.
vám-ért	Duty	fém-ért	metal	Caus.
hám-ért	harness	hím-ért	dog	Caus.
púp-ért	Hump	pép-ért	cream of wheat	Caus.

e

totem-mal	Totem	tetem-mel	dead body	Inst.
totem-tól	Totem	tetem-től	dead body	Abl.
hárem-ban	Harem	érem-ben	medal	Iness.
hárem-mal	Harem	érem-mel	medal	Inst.
hárem-on	Harem	érem-en	medal	Superess.
hárem-ba	Harem	érem-be	medal	Illat.
hárem-ból	Harem	érem-ből	medal	Elat.
hárem-hoz	Harem	érem-hez	medal	Allat.

Frame sentences
Azt mondom, hogy ____ és elismétlem azt, hogy ____ mégegyszer.
'I say ____ and I repeat ____ once again.'
Ekkor azt láttam, hogy ____ akkor pedig azt láttam, hogy ____ mégegyszer.
'Now I see ____ and then I read ____ once again.'

Appendix C

Post hoc tukey test: effect of vowel type on the tongue position in the front and back harmonic types, EMMA

Multiple comparisons, subject ZZ, FRONT H-TYPE

Receiver	(I) T. VOWEL	(J) T. VOWEL	Mean difference (I–J)	Std. error	Sig.
TD	/i/	/iː/	.233821	.1914347	.441
		/eː/	−.989083(*)	.1914347	.000
	/iː/	/i/	−.233821	.1914347	.441
		/eː/	−1.222904(*)	.1896864	.000
	/eː/	/i/	.989083(*)	.1914347	.000
		/iː/	1.222904(*)	.1896864	.000
TB2	/i/	/iː/	−.297614	.2941172	.570
		/eː/	−2.057903(*)	.2941172	.000
	/iː/	/i/	.297614	.2941172	.570
		/eː/	−1.760289(*)	.2914311	.000
	/eː/	/i/	2.057903(*)	.2941172	.000
		/iː/	1.760289(*)	.2914311	.000
TB1	/i/	/iː/	−.786079(*)	.3089814	.031
		/eː/	−1.901592(*)	.3089814	.000
	/iː/	/i/	.786079(*)	.3089814	.031
		/eː/	−1.115513(*)	.3061596	.001
	/eː/	/i/	1.901592(*)	.3089814	.000
		/iː/	1.115513(*)	.3061596	.001

Multiple comparisons, subject ZZ, BACK H-TYPE

Dependent variable	(I) T. VOWEL	(J) T. VOWEL	Mean difference (I–J)	Std. error	Sig.
TD	/i/	/iː/	−.792725(*)	.2379112	.003
		/eː/	−1.291158(*)	.2379112	.000
	/iː/	/i/	.792725(*)	.2379112	.003
		/eː/	−.498433	.2467439	.109
	/eː/	/i/	1.291158(*)	.2379112	.000
		/iː/	.498433	.2467439	.109
TB2	/i/	/iː/	−2.134391(*)	.3458925	.000
		/eː/	−2.461490(*)	.3458925	.000
	/iː/	/i/	2.134391(*)	.3458925	.000
		/eː/	−.327099	.3587340	.633
	/eː/	/i/	2.461490(*)	.3458925	.000
		/iː/	.327099	.3587340	.633
TB1	/i/	/iː/	−2.790666(*)	.3756004	.000
		/eː/	−1.995064(*)	.3756004	.000
	/iː/	/i/	2.790666(*)	.3756004	.000
		/eː/	.795602	.3895449	.104

	/eː/	/i/	1.995064(*)	.3756004	.000
		/iː/	−.795602	.3895449	.104

Post hoc Tukey and test: effect of vowel category on the tongue position in the front and back harmonic type words, ultrasound

Multiple comparisons, subject ZZ

H-TYPE	(I) T.VOWEL	(J) T.VOWEL	Mean difference (I–J)	Std. error	Sig.
Front	/i/	/iː/	.06664(*)	.01433	.000
		/eː/	.05447(*)	.01433	.000
	/iː/	/i/	−.06664(*)	.01433	.000
		/eː/	.12111(*)	.01480	.000
	/eː/	/i/	−.05447(*)	.01433	.000
		/iː/	−.12111(*)	.01480	.000
Back	/i/	/iː/	−.03730(*)	.01372	.018
		/eː/	−.05195(*)	.01372	.000
	/iː/	/i/	.03730(*)	.01372	.018
		/eː/	−.01466	.01412	.553
	/eː/	/i/	.05195(*)	.01372	.000
		/iː/	.01466	.01412	**.553**

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