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Vowel harmony: transparent and opaque vowels

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1. Introduction

In linguistic theory, there is a tension between two core aims of the field: theoretical parsimony and empirical coverage of the remarkable diversity and specificity seen in linguistic data. Vowel harmony[1] and more specifically the two phenomena of transparency and opacity in vowel harmony which concern us in this paper provide prime examples of phonological research concerned with resolving this tension. Recent findings and promising new theoretical ideas on transparency and opacity indicate that our understanding of these phenomena is at a critical stage. The crucial future step will be the integration of the new data patterns with insights from theoretical analyses. This would require an improved understanding of the phonetic basis of vowel harmony, the nature and origin of the grammatical forces governing transparency and opacity, and finally an understanding of the organizational principles governing the resolution of these forces within and across languages.

2. Definitions and exemplification of the basic patterns

Vowel harmony is a regularity found in many languages requiring vowels in certain grammatical domains to agree in terms of specific phonological features. For example, the vowels of Hungarian can be divided into two subsets, the ‘front’ vowels /i í e é ö ő ü ű/ and the ‘back’ vowels /u ú o ó a á/ (Vago 1980, van der Hulst 1985, Siptár & Törkenczy 2000; see also Törkenczy, this volume). In terms of phonological features, the vowels in the ‘front’ set share the feature [–back] and vowels in the ‘back’ set share the feature [+back]. In Hungarian, the existence of vowel harmony is most readily observed in suffix vowel alternations where the [±back] quality of the suffix vowel is determined by the [±back] quality of the stem vowel. For example, as shown in (1), the Dative suffix alternates between two forms, one with the front /e/ and another with the back /a/, as a function of the stem vowel: *ház-nak* ‘house-DATIVE’, *város-nak* ‘city-DATIVE’, but *kéz-nek* ‘hand-DATIVE’, *öröm-nek* ‘joy-DATIVE’ (in Hungarian orthography, the acute accent denotes a long vowel, the umlaut denotes front round vowels, and the double acute indicates long front round vowels). In such combinations of stems and suffixes, then, the suffixes adjust or harmonize to the [±back] ‘harmonic feature’ of the stem vowels. Because it determines the suffix form, the stem vowel is called the trigger and the suffix vowel is called the target of the harmony pattern.

(1) Regular vowel harmony

Stem vowels are front ([–back])		**Stem vowels are back** ([+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

[1] For two excellent reviews of vowel harmony, see Archangeli & Pulleyblank (2007) and van der Hulst & van der Weijer (1995). See Gordon (2006) for a short article on the phonetics of transparency harmony. At the introductory level, a cogent discussion of different proposals on vowel harmony can be found in Kenstowicz (1994). For recent dissertation-length treatments of vowel harmony see Baković (2000), Kramer (2003) and Przezdziecki (2005).

A central aim in phonological theory has been to characterize the range and possible forms of such systematic sound patterns in different languages (Chomsky & Halle, 1968). A particularly fruitful research strategy in this regard has been to explore the *phonetic basis* of sound patterns, that is, the extent to which such patterns can be seen as adaptations to biological constraints on speech production and perception (Lindblom 1983, cf. Anderson 1981). For vowel harmony, it has been proposed that a natural basis for it can be traced to the low-level phonetic influences among vowels in consecutive syllables (Fowler 1983, Ohala 1994a-b, Beddor *et al.* 2001, Przezdziecki 2005). The crucial fact is that vowels exert influences on neighboring vowels across intervening consonants, the so-called *V-to-V coarticulation* (Öhman 1966). Acoustically this means that in a [V1CV2] sequence, V2's formant values are influenced by the identity of V1. Articulatorily, the basis of this phenomenon is well understood. Vowels are produced by movements of the tongue body and the jaw, with relatively slow changes in the global shape of the vocal tract because of the larger mass involved. In the case of a [V1CV2] sequence, while the consonantal constriction is localized at some area in the vocal tract, the free part of the tongue is allowed to assume different shapes and thus move in a "smooth transition" (Öhman 1966) from the shape of the first vowel to the shape of the second vowel. Vowels, in other words, provide a continuous articulatory substrate over which consonants are superimposed. V-to-V coarticulation is a direct consequence of this articulatory continuity. This phonetic effect can develop, via processes of phonologization, into vowel harmony (Hyman 1976, Przezdziecki 2005).

However, within the attested range of phonological vowel harmony patterns there exist phenomena that are systematic yet unexpected given the phonetic grounding sketched above. Specifically in Hungarian, but also in other languages with vowel harmony, one also finds a set of so-called neutral vowels that do not undergo harmony. Neutral vowels come in two species, transparent and opaque. The most well-known property of transparent vowels is that they may intervene between the trigger and the target vowel even when they bear the opposite value for the harmonizing feature. The examples in (2) show that the first stem vowel dictates the backness value for the suffix vowel across the intervening transparent vowels {*í* [iː], *i* [i], *é* [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 seem to establish a harmony relationship across both consonants and transparent vowels.

(2) Transparent vowels: agreement across the medial vowel

First stem vowel is front		**First stem vowel is 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* [guminɔk]	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

The other species of neutral vowels, opaque vowels, block harmony by overriding the expected consequences of another potential trigger in the phonological form. Thus, for example, whereas the front unround Hungarian vowels are transparent, front round vowels in Hungarian and other palatal vowel harmony systems are opaque, e.g. *papír-nak* 'paper-DATIVE' vs. *parfüm-nek* 'perfume-

DATIVE’. In the latter form, the front round ‘*ü*’ [y] initiates its own harmony domain, imposing a [–back] specification on its following suffix.

Whereas the existence of opaque vowels is consistent with the generally accepted idea that the phonetic basis of vowel harmony inheres in V-to-V coarticulation effects, transparent vowels pose a challenge to that idea. Consider, for example, the difference in the suffix vowels between words like *papír-nak* ‘paper-DATIVE’ and *zefír-nek* ‘zephyr-DATIVE’. The backness of the suffix in these words must be linked to the backness 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 [i:] is resistant to coarticulation from the preceding vowel(s) in terms of perception (e.g. Recasens 1987 for Spanish and Catalan, Farnetani *et al.* 1985 for Italian, Magen 1984 for Japanese). As we will see in section 3, because of this long-distance character, transparency has been a recalcitrant problem in theoretical treatments of the phenomenon.

A notable generalization in ‘palatal’ vowel harmony systems is the existence of a 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).[2] Hence, stems such as *hotel* vacillate: *hotel-nak/nek* ‘hotel-DATIVE’; but stems such as *papír* do not vacillate: *papír-nak*, **papír-nek* ‘paper-DATIVE’. Thus, the generalization is that the lower and more retracted [ɛ] is phonologically less transparent than the higher and more front [i] (see Benus 2005 for characterizations of these vowels based on ultrasound and electromagnetic articulometry data). A similar generalization is true for Finnish and other palatal vowel harmony systems (L. Anderson 1980). 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.

Another notable generalization concerns the relationship between suffix choice and the number of transparent vowels in stems: stems where a back vowel is followed by two transparent vowels are more likely to vacillate or take front suffixes than stems where a back vowel is followed by only one transparent vowel. For example, *mam-i* and *mam-csi* (both forms mean ‘mom-DIMINUTIVE’) select back suffixes: *mami-nak*, *mamcsi-nak* ‘mom-DIMINUTIVE-DATIVE’. However, when the two diminutive suffixes are combined in *mamicsi*, both front and back suffixes are acceptable: *mamicsi-nak/nek* ‘mom-DATIVE’ (Farkas & Beddor 1987, Ringen & Kontra 1989, Kaun 1995, Benus 2005, Hayes & Londe 2006). Benus (2005), highlighting this aspect of the Hungarian data, concludes that 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*). The generalization that the number of transparent vowels affects suffix selection has been difficult to express in analyses where transparent vowels are assumed to be skipped or invisible in vowel harmony. The problem for these analyses should be clear. If one excludes transparent vowels from participating in harmony, then their number should not affect suffix choice, contrary to what the data tell us.

Our examples of transparency and opacity so far come from a so-called **‘palatal’ vowel harmony** system where, following standard description, the phonological feature exhibiting harmonic behavior is [±back]. Transparency and opacity can be instantiated regardless of the vowel

[2] This statement is a first approximation to a set of complex data patterns. Farkas & Beddor (1987), Kaun (1995), Benus (2005), Benus & Gafos (2007), and Hayes & Londe (2006) provide details, data, and relevant discussion on this height-transparency link in Hungarian.

feature exhibiting harmony. In what follows, we exemplify the other major classes of harmony: 'tongue root' harmony, 'rounding' harmony and 'height' harmony.

'Tongue root' harmony. In languages described as having 'tongue root' harmony, vowels harmonize for features that correspond to the position of the tongue root or pharyngeal expansion/compression. In these languages, following common phonological description, vowels may be 'advanced', articulated with the tongue root in an advanced position, or 'retracted', articulated with a non-advanced or retracted tongue root. The relevant phonological dimension of distinction, it has been proposed, is [±ATR] (originally from Halle and Stevens 1969) with advanced vowels sharing [+ATR] and retracted vowels [–ATR]. This is a standard way of describing the phonetic basis and the phonological feature in question. But work by Lindau (1978), using radiographic and acoustic data, and by Tiede (1996) using MRI data, indicates that the relevant difference is in terms pharyngeal expansion versus compression, which can be achieved in different ways one of which is by positioning the tongue root in the way implicated by [±ATR]. At a first approximation, however, we can talk about patterns of transparency and opacity in 'tongue root' harmony without being precise about the phonetic dimensions involved. Thus, our first example of 'tongue root' harmony comes from Akan (Schachter and Fromkin 1968, Ladefoged 1964, Lindau 1978, Dolphyne 1988). As can be seen in the personal pronoun – stem combinations shown in (3), each pronoun prefix alternates between two forms, a [+ATR] form shown in the left column and a [–ATR] form shown in the right column. Here, as in Hungarian, the stem determines the exact form of the affix, but it is the [ATR] value as opposed to the [back] value, in the case of Hungarian, that is being determined by the stem. In the left column, the verb *di* 'to eat,' which contains a [+ATR] vowel, imposes that value to the prefix so that we get forms such as *mi-di* 'I eat' and *wu-di* 'you eat'. By contrast, the verb *dɪ* 'to be called' imposes its [–ATR] value to its prefix, so that the same prefixes surface as *mɪ-dɪ* 'I am called' and *wʊ-dɪ* 'you are called'.

(3) Akan vowel harmony

[+ATR]		[–ATR]	
a. mi-di	'I eat'	f. mɪ-dɪ	'I am called'
b. wu-di	'you eat	g. wʊ-dɪ	'you are called'
c. o-di	'he eats'	h. ɔ-dɪ	'he is called'
d. ye-di	'we eat'	i. yɛ-dɪ	'we are called'
e. wo-di	'they eat'	j. wɔ-dɪ	'they are called'

In Akan, as can be seen above, both high and mid vowels are subject to harmony, but in other tongue root harmony languages, the vowels which alternate comprise a more restricted set. In these latter languages, mid vowels alternate and high vowels are transparent. Thus, in Wolof only the mid vowels /e/, /ɛ/, /o/, /ɔ/ alternate in harmony. In the examples shown in (4) below, [–ATR] stems take the *–ɔɔn* and [+ATR] stems take the *–oon* form of the past tense suffix.

(4) [ATR] harmony in Wolof (data from Archangeli and Pulleyblank 1994, Pulleyblank 1996)

[–ATR]		[+ATR]	
a. rɛɛr-ɔɔn	'had dinner'	d. reer-oon	'was lost'
b. takk-ɔɔn	'tied'	e. bəgg-oon	'wanted'

c. jɔx-ɔɔn ‘gave’ -oon ‘came’

In Wolof, the high vowels are neutral (Archangeli and Pulleyblank 1994). In particular, high vowels in Wolof are transparent to vowel harmony.[3] In (5), the initial stem vowels determine the [ATR] values of the suffix vowels across the medial transparent vowels. In the left column, stems with initial [+ATR] vowels take [+ATR] suffixes. In these cases the intervening high vowel has the same feature value, but in the right column the opposite is true. In the forms on the right, stems with [–ATR] vowels take [–ATR] suffixes, despite the fact that the intervening high vowel has the opposite feature value for ATR.

(5) Transparent vowels in Wolof (Archangeli and Pulleyblank 1994)

a. toxi-leen	‘go & smoke’	g. tɛkki-lɛɛn	‘untie!’
b. gəstu-leen	‘do research!’	h. mɔytu-lɛɛn	‘avoid!’
c. təriji-leen	‘go sleep!’	i. sɔppiwu-lɛɛn	‘you have not changed’
d. təri-woon	‘went & slept’	j. xɔlli-wɔɔn	‘peeled’
e. seenu-woon	‘tried to spot’	k. tɛɛru-wɔɔn	‘welcomed’
f. yobbu-jinə	‘he went to bring’	j. yɛbbi-jina	‘he went to unload’

Archangeli and Pulleyblank (1994) highlight a plausible phonetic basis for the markedness of [ATR] contrasts within high vowels in languages like Wolof. Raising of the tongue body, which is required for [+high] vowels, and advancing of the tongue root, which is required for [+ATR] vowels, are compatible gestures. Both of these gestures serve to lower F1, producing the percept of a higher vowel. In the same way, lowering of the tongue body and retracting the tongue root are compatible, and in concert they help create a perceptually lower vowel by producing a higher F1. Tongue body raising/ tongue root retraction and tongue body lowering/tongue root advancement, however, are pairs of incompatible gestures, because one member of each pair serves to counteract the acoustic effect of the other. This phonetic basis provides plausible reasons for the lack of [+high, –ATR] vowels contrasting with the transparent vowels of Wolof.

Archangeli and Pulleyblank (1994) further propose that the lack of contrast may underlie the transparency of these vowels. That is, in Wolof, the non-contrastiveness of [+high, –ATR] vowels is reflected in their neutrality to vowel harmony. In languages where [+high, –ATR] vowels are contrastive, however, these vowels participate in vowel harmony. Lindau (1978) shows that, in Akan, the [+high, –ATR] vowel /ɪ/ is acoustically very similar to the [–high, +ATR] vowel /e/, but /ɪ/ remains phonemically distinct from /e/, and as shown above, the Akan high vowels do participate in vowel harmony in the same way as mid vowels.[4] The reader is referred to Archangeli and

[3] High-vowel-initial roots are always harmonic (for [+ATR]) in Wolof, but this is the only circumstance in which high vowels trigger harmony.

[4] If their acoustics are so similar, how do listeners acquire the difference between /ɪ/ and /e/? Lindau proposes that learners pick up the generalization that the vowel space of their ambient language can be organized in pairs where the distinctions within each pair have a clear articulatory basis. We have been describing this basis as expressed by the phonological feature [±ATR] but for Lindau the feature is called [Expanded]. We suggest the following learning scenario: some vowels across different pairs such as /ɪ/ from the pair /i, ɪ/ and /e/ from the pair /e, ɛ/ may surface with indistinguishable or similar acoustics. The presence of harmony, which imposes vowel alternations as in [i]~[ɪ] and

Pulleyblank (1994) who discuss other cases of cross-linguistically variable behavior of [+high, –ATR] vowels in vowel harmony.

Like high vowels, low vowels may also be neutral. In Pulaar, for instance, low vowels are opaque to vowel harmony. Pulaar shows regressive harmony of mid vowels, such that the [ATR] value of suffixes migrates to stems, as in *peec-i* / *pɛɛc-ɔn* 'crack PL. / crack DIM. PL.' where the plural suffix *–i* causes the stem to surface with a [+ATR] vowel, while the diminutive plural suffix *–ɔn* imposes its [–ATR] value onto the stem. The behavior of mid vowels may be contrasted with that of the opaque low vowel /a/ exemplified in (6) below.

(6) Opaque low vowels in Pulaar (Archangeli and Pulleyblank 1994)

a. bɔɔt-aa-ri	'dinner'	a'. *boot-aa-ri
b. pɔɔf-aa-li	'breaths'	b'. *poof-aa-li
c. nɔdd-aa-li	'call'	c'. *nodd-aa-li
d. ᵑgɔr-aa-gu	'courage'	d'. *ᵑgor-aa-gu

In (6), the [+ATR] value of the rightmost suffix cannot spread to the low vowel /a/, which surfaces as [–ATR] everywhere in Pulaar. The low vowel not only does not accept the feature value of the suffix to its right, but it blocks vowel harmony from propagating to the stem to its left, and starts its own harmonic domain, as shown by the starred examples (6)a'-d'; when a stem appears to the left of /a/, it cannot contain a [+ATR] vowel.

Phonetic factors have also been implicated in grounding the phenomenon of opacity in 'tongue root' harmony systems (Archangeli and Pulleyblank 1994). As discussed above, lowering the tongue body for a low vowel is compatible with retracting the tongue root to produce a [–ATR] vowel. Both of these gestures serve to raise F1, producing the percept of a low vowel. Conversely, lowering the tongue body and advancing the tongue root, which have opposite effects on F1, are antagonistic gestures. The articulatory incompatibility of tongue body lowering and tongue root advancement is reflected in a cross-linguistic tendency for [+low] vowels to be [–ATR]. This phonetic basis for the markedness of [+low, +ATR] vowels may underlie their propensity to be neutral to harmony in languages such as Pulaar above. Lindau (1978) points out that 'tongue root' harmony languages commonly have one neutral vowel, a low vowel. Anderson (1980) also discusses the tendency of languages to restructure their vowel inventories by neutralizing the ATR contrast in low vowels first (before neutralizing this contrast in other vowels) in the context of African and Paleosiberian languages.

We have thus seen that the phonetic markedness of [+high, –ATR] and [+low, +ATR] vowels has been argued to bear on the neutrality of [+high, +ATR] and [+low, –ATR] vowels. As is often the case with phonetic motivations for phonological patterns (Anderson 1981), identifying plausible phonetic grounds for neutrality does not fully explain the behavior of neutral vowels in these harmony systems. The fundamental question is: what principles determine when a vowel is

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[e]~[ɛ], coupled with the well-defined articulatory basis for the contrast across different pairs, can disambiguate the phonemic class of the near identical [ɪ], [e]. When observed in alternations, phonetic tokens from the allophones [ɪ], [e] alternate with vowels that are clearly distinguishable, [i] and [ɛ], respectively. The presence of harmony facilitates the learning of the distinction.

transparent or opaque? Consider the case of Wolof, in which high vowels are transparent to vowel harmony but, in some circumstances, the low vowel may be opaque.[5] There exist plausible phonetic grounds for saying that both [+high, –ATR] and [+low, +ATR] vowels are marked. But it has remained unclear how exactly these similar markedness considerations are translated into the different phonological behavior these vowels seem to exhibit.

We can highlight the issue of how deterministic phonetic forces may be of phonological behavior when we also consider that what appears to be the same vowel may be transparent in some languages but opaque in others. For example, in Pulaar, as described above, and Tangale (van der Hulst and van de Weijer 1995, Kidda 1985, Jungraithmayr 1971) the low vowel /a/ is opaque. Pulaar and Tangale differ crucially from Kinande (Cole and Kisseberth 1994, Schlindwein 1987, Steriade 1987, Mutaka 1995) wherein /a/ is transparent to vowel harmony. Compare Kinande *tu-ka-ki-lim-a* 'we exterminate it,' in which the morpheme *-lim-* is the trigger for spreading [+ATR] leftward, across /a/ to *tʊ-ka-kɪ-lɪm-a* 'we cultivate it,' in which *-lɪm-* triggers [–ATR] spreading across the intervening /a/ (Cole and Kisseberth 1994). Predicting the transparency vs. opacity of /a/ in these languages cannot be reduced to a question of phonological contrast, since /a/ has no phonological [+ATR] counterpart in any of the relevant languages. On the surface, then, the cross-linguistically variable behavior of neutral /a/ seems to present a puzzle. However, recent articulatory work (Gick et al. 2006) suggests that the real question may not be one of opacity vs. transparency, but opacity vs. participation in harmony, showing that /a/ in Kinande is categorically affected by vowel harmony.

'Rounding' harmony. In various languages, including those of the Turkic, Mongolian, and Tungusic families, as well as Yawelmani (now called Yolumne), an American Indian language of California, vowels harmonize for lip posture. As we remarked for the case of 'tongue root' harmony, the phonetic basis of the harmonizing 'rounding' feature is a separate non-trivial issue (see Goldstein 1991). With this in mind, we will follow standard description in saying that the feature showing harmony in these languages is [± round]. In Turkish 'rounding' harmony, both high and non-high vowels can trigger rounding harmony, but only high vowels are eligible as targets. The first person singular possessive suffix, for example, alternates depending on the value of the stem for the feature [round], as shown in (7).

(7) High vowel suffixes alternate in Turkish

a.	ip	'rope'	ip-im	'my rope'
b.	süt	'milk'	süt-üm	'my milk'
c.	ev	'house'	ev-im	'my house'
d.	čöp	'garbage'	čöp-üm	'my garbage'
e.	kız	'girl'	kız-ım	'my girl'
f.	buz	'ice'	buz-um	'my ice'
g.	at	'horse'	at-ım	'my horse'
h.	gol	'goal'	gol-um	'my goal'

[5] The long low vowel /a:/ is always opaque in Wolof, but short /a/ usually participates in vowel harmony. There are exceptions to the behavior of short /a/, however, in which it is also opaque. See Archangeli & Pulleyblank (1994) for thorough discussion.

In the examples in (7), stems with [–round, –back] vowels take the *–im* form of the suffix, stems with [–round, +back] vowels take the *–ım* form, stems with [+round, –back] vowels take the *–üm* form of the suffix, and stems with [+round, +back] vowels take the *–um* form of the suffix. The behavior of the high vowel suffix in (7) may be contrasted with that of the dative suffix, *-e/-a*, which, like other non-high suffixes, does not participate in rounding harmony. In (8), stems containing a front vowel take the *–e* form of the dative, and those containing a back vowel take the *–a* form. There are no rounded versions of the dative suffix.

(8) Low vowel suffixes do not alternate in Turkish

a.	ip	'rope'	ip-e	'rope-DAT'	
b.	süt	'milk'	süt-e	'milk-DAT'	*süt-ö
c.	ev	'house'	ev-e	'house-DAT'	
d.	čöp	'garbage'	čöp-e	'garbage-DAT'	*čöp-ö
e.	kız	'girl'	kız-a	'girl-DAT'	
f.	buz	'ice'	buz-a	'ice-DAT'	*buz-o
g.	at	'horse'	at-a	'horse-DAT'	
h.	gol	'goal'	gol-a	'goal-DAT'	*gol-o

Non-high vowels in Turkish are, in fact, opaque to rounding harmony. In (9), the interrogative suffix *mi*, which contains a high vowel and is normally subject to rounding harmony in exactly the same pattern as the first person singular possessive suffix, does not alternate because an intervening opaque vowel (the dative suffix) blocks harmony from the stem.

(9) Non-high vowels are opaque to rounding harmony in Turkish

a.	ip-e mi	'is it rope-DAT?'	
b.	süt-e mi	'is it milk-DAT?'	*süt-e mü
c.	kız-a mı	'is it girl-DAT?'	
d.	buz-a mı	'is it ice-DAT?'	*buz-a mu

These examples show that forms like **süt-e mü?* 'is it milk-DAT?' are impossible. Though normally a stem like *süt* would trigger rounding harmony for a suffix containing a high vowel, this harmony is blocked by the intervening dative suffix, which contains a non-high vowel. Another well-known example of the interaction between vowel height and rounding harmony is found in Yawelmani (Kenstowicz and Kisseberth 1979). In Yawelmani, rounding harmony only occurs between vowels of the same height. For example, a stem containing a high vowel will only trigger harmony with a following high vowel: compare *dub-nut* 'will be led by the hand' with *bokˀ-nit* 'will be found.' Similarly, a non-high vowel can only trigger harmony with a following non-high vowel, as in *bokˀ-xo* 'let us find' vs. *dub-xa* 'let us lead by the hand.'

Kaun (1995) offers an account of facts like these in terms of a constraint called UNIFORM[RD]. This constraint states that [+round] cannot be linked to multiple vowel positions which differ from each other in height. If the rounding gestures of high vs. non-high vowels are different, as Linker (1982) argues, then the association of a single [+round] feature with vowels of different heights would result in multiple articulatory configurations associated with one feature. In Kaun's system this is interpreted as a violation of UNIFORM[RD]. This constraint encodes the sensitivity of harmony systems to the height-rounding interactions revealed in Kaun's typological study.

A well-known case of transparency in rounding harmony is observed in Khalkha Mongolian. In the rounding harmony of this language, [+round] extends rightward from a stem to an eligible suffix vowel. Transparency is observed in the examples in (10) where a /i/ intervenes between a stem vowel and a suffix target vowel (data from Svantesson et al. 2005). In examples (10)a, b, c, the [+round] feature of the stem spreads across /i/ to a suffix vowel. Examples (10) d, e, f show that these suffix vowels surface as [–round] when the initial stem vowel is [–round].

(10) Transparent [i] in the rounding harmony of Khalkha Mongolian

a.	poor-ig-o	'kidney.ACC.RFL'	d.	piir-ig-e	'brush.ACC.RFL'
b.	xɔɔʦ-ig-ɔ	'food.ACC.RFL'	e.	teeʦ-ig-e	'gown.ACC.RFL'
c.	ɔʦʲi-ʦɔ	'to squint.DPST'	f.	tʰaxʲi-ʦa	'to be bent.DPST'

Previous theoretical discussions of Mongolian rounding harmony (Anderson 1980, Steriade 1995) have considered the transparency of /i/ to be problematic. As we discuss in the following section, a popular account of transparency in vowel harmony when applied to our example, [poor-ig-o], would maintain that rounding is first transmitted to all vowels in this word, including the transparent vowel /i/. This is a standard way to express formally the intuition that the rounding of the suffix vowel is due to the rounding of the first stem vowel in [poor-ig-o] while respecting one of the fundamental phonological principles that such dependencies among phonemes in words are local. As a result of this step, however, the intermediate representation obtained is [*poor-yg-o*], where the transparent vowel has changed to an [y]. In order to derive the correct surface form, this intermediate form would need to be repaired via a rule like [y] → [i]. However, such a rule is not tenable in the case of Mongolian, because /y/ is thought to be a phoneme of the language, and there is no principled way to distinguish derived [y] from underlying /y/ in the application of such rules. However, Rialland & Redouanne's (1984) as well as Svantesson et al.'s (2005) acoustic data show that the phoneme notated with /y/ in past analyses is not a front vowel. Therefore, /i/ and /y/ are not phonemically contrastive in this language. Rather, the data show that the purported [y] is a back vowel. In the light of the phonetic evidence, then, this case of transparency is not as unique as it was thought to be. As we seen in the cases of transparency in 'palatal' and 'tongue root' harmony systems reviewed so far, the transparent vowels do not contrast with respect to the harmonizing feature, e.g. /i/ in Hungarian does not have a back counterpart, /i/ in Wolof does not have a [–ATR] counterpart, and /a/ of Kinande does not have a [+ATR] counterpart.

Kaun (1995) proposes a phonetic basis for rounding harmony in terms of perceptual salience. She argues, following Lindblom (1975, 1986), that vocalic contrasts which are manifested in F1 frequency (i.e. height contrasts) are more perceptually salient than those contrasts which are acoustically manifested in F2 frequency (i.e. backness and rounding). The relevant perceptual-acoustic difference between F1 and F2 is taken to be intensity. F1 is more intense, and thus more resistant to noise and more perceptually salient, than F2 and the higher formants (Lindblom 1986). Kaun argues that some languages employ rounding harmony in order to counteract the overall lower perceptual salience of backness and rounding contrasts along the following lines. Because back vowels are associated with low F2 values, and lip-rounding lowers formants in general, it can be said that backness serves to perceptually enhance a round vowel by reinforcing its low F2 value.

Similarly, roundness enhances the percept of backness by reinforcing a low F2 value (Stevens, Keyser, and Kawasaki 1968). By the same token, the formant-lowering effects of lip rounding are detrimental for front vowels, which need to maintain a higher F2. These facts are reflected in the cross-linguistic preference for vowel inventories in which the values for [round] and [back] are redundant (i.e. languages containing front unround vowels and back round vowels). In a smaller number of languages, the features [round] and [back] are not redundant, and in such languages the perceptual cues for recovering backness and rounding values will be weaker, since these cues are not being used to enhance one another. Kaun (1995) argues that rounding harmony often appears in these languages. The functional reason is that harmony repeats the same value for the feature [round] across the entire word or harmonic domain. Such extension of a single feature value for [round] across a domain larger than a single segment improves chances of perceiving and correctly identifying that feature (see also Suomi 1983 who promotes a similar idea for 'palatal' harmony systems).

'Height' harmony. Languages may also show vowel harmony in terms of 'height'. In phonological terms, these systems require uniformity across vowels in terms of the phonological feature [±high]. Some instances of what have been called 'height' harmony systems have been an issue of discussion in connection with 'tongue root' harmony. This issue arises because tongue body vertical position, an undisputed correlate of phonological height, and pharyngeal size have very similar effects in the frequency of the first formant -- see Lindau (1978) for particularly clear illustration of this from Akan. As an expected consequence, then, in some harmony systems such as that of Kinande, the harmonic classes seem to differ according to vowel height as well as tongue root position. Clements (1990, 1991) proposes an account for such systems in terms of an 'aperture' theory of vowel height. In his theory, the harmonic classes are distinguished based on their value for the feature [open], used to implement height distinctions. More recent discussion of the same issue, 'tongue root' versus 'height' harmony, can be found in the instrumental studies of Gick et al. (2006) and Kenstowicz (2009) who provide converging evidence in favor of the 'tongue root' interpretation for the Kinande vowel harmony system.

In part because of this issue, the height harmony systems we chose to exemplify below come from dialects of Italian – these systems have not received an interpretation in terms of 'tongue root' harmony and thus can be considered as good representatives of 'height' harmony (see van der Hulst and van de Weijer 1995 for further relevant discussion of the 'tongue root' versus 'height' harmony issue). This position must be qualified as tentative. The phonetic bases of the distinctions implicated in the Italian vowel harmony systems below have not been the subject of systematic studies. Additionally, the application of harmony in these languages depends on non-local information in the following way. In most vowel harmony languages, feature spreading from one segment to an adjacent segment takes place regardless of the eligibility of a subsequent segment to undergo the feature-spreading. In these canonical systems, the relationship between harmony trigger and target is essentially local. In the vowel harmony systems of Northern Italian dialects, which form a typological complement to the systems we have already discussed, a feature only spreads from one segment to an adjacent segment when there is also a viable non-local target for harmony.

Dialects spoken in Italy's central Veneto region and the island of Grado show a type of height harmony in which a post-tonic high vowel triggers raising of a stressed mid vowel (Walker 2005, 2010). In Central Veneto and Grado, a post-tonic high vowel causes /e/, /o/ to raise to [i], [u], respectively. Commonly, harmony is triggered by an inflectional suffix, as shown in (11). All of the Central Veneto and Grado data in this section is taken from Walker (2010).

(11) Height harmony triggered by suffixes

Central Veneto

a.	kals-ét-o	kals-ít-I	‘sock (M. SG./PL.)’
b.	kant-é-se	kant-í-si-mo	‘sing (1SG./1PL. IMPF. SUBJ.)’
c.	móv-o	múv-i	‘move (1SG./2SG.)’
d.	botón	botún-i	‘button (M. SG./PL.)’

Grado

e.	kré-e	krí-i	‘believe (3SG./2SG.)’
f.	benedét-o	benedít-i	‘blessed (M. SG./PL.)’
g.	rómp-o	rúmp-i	‘break (1SG./2SG.)’
h.	albor-ét-o	albor-ít-i	‘tree (M. SG./PL. DIMIN.)’

The data in (11) illustrates the basic pattern of vowel harmony in the dialects of interest here. Harmony is triggered by suffix vowels and may only target stressed vowels. If trigger and target are not adjacent, the intervening vowels must also undergo harmony. In (11)a, the plural suffix *–i* causes the stressed mid vowel in *kalsét* to raise, giving the surface form *kalsíti*, and in (11)c the second person singular suffix *-i* causes the stressed mid vowel in *móv-* to raise, resulting in the surface form *muvi* ‘you move.’ (11)f shows that harmony targets stressed vowels but does not apply past a stressed vowel; the plural suffix gives the surface form *benedíti* from underlying *benedét-* and not **binidíti*. In the examples above, harmony is triggered by a vowel adjacent to the target, but in Central Veneto and Grado harmony harmony can also be triggered by a vowel which is not adjacent to its target. For example, consider Grado *énzen-e* ‘shin (M.SG.)’ vs. *ínzin-i* ‘shin (M.PL.)’ and *zóven-e* ‘young man (SG.)’ vs. *zúvin-i* ‘young man (PL.)’. In these pairs, harmony is triggered by a suffix onto a stressed vowel target in the stem, but the intervening vowels must also undergo harmony. Thus, in *ínzin-i*, we see that the plural suffix *–i* causes *énzen-* to surface as *ínzini* ‘shins’ instead of **ínzeni*. The general pattern, then, is one where harmony applies regressively from the trigger to a stressed vowel target, affecting eligible vowels between trigger and target but not subsequent vowels (see the Grado examples in this paragraph and (11)f).

Harmony may also be blocked when a low vowel intervenes between trigger and target. This opacity of low vowels appears in Central Veneto, in forms like *la(v)ór-a-v-a* ‘worked/was working (1SG.)’ vs. *la(v)ór-a-v-i* ‘worked/was working (2SG.)’ In these cases, *ó* is an eligible target and the second person singular imperfect suffix *–i* is an eligible trigger, but the presence of the intervening opaque low vowel blocks the transmission of height harmony.

Though the dialects in Walker’s (2005, 2010) study do not show transparent vowels, they do appear in other height harmony languages. One example comes from the Italian dialect of Ascrea. In Ascrea, mid vowels undergo harmony in words in which trigger and target are adjacent, as in ‘deaf’ from *-u.* When an unstressed mid vowel intervenes between trigger and target, it is transparent to harmony. Compare the forms *tóreu-a* ‘cloudy (F.SG.)’ and *túreu-u* ‘cloudy (M.SG.)’ (data from Fanti 1938, 1939, 1940, cited in Walker 2010). Here, the masculine singular suffix *–u* triggers harmony of the stressed stem vowel *ó*, but the intervening mid vowel *e* is unaffected. Compare this form to those in (11), which show that in Central Veneto and Grado, mid vowels which occur between trigger and target undergo harmony. The difference between these languages is that, in Ascrea, only stressed target vowels may undergo harmony, whereas in Central Veneto and Grado, both target vowels and intervening vowels may undergo harmony.

The work on these height harmony systems is much more recent than that for the ‘palatal’, ‘tongue root’ and ‘rounding’ harmony systems discussed in previous sections. As such the potential phonetic basis for this kind of harmony has not been explored in depth. Walker (2010) proposes a phonetic basis to height harmony along the lines of Kaun's (1995) proposals for rounding harmony. The proposal is that height harmony is motivated by a need to improve the perceptibility of a feature which would be difficult to identify in the absence of harmony. Walker argues that the triggers of height harmony, unstressed high vowels, are perceptually weak because high vowels are lower in amplitude than other vowels, and tend to be shorter in duration than non-high vowels (Meyer 1903, House and Fairbanks 1953, Wells 1962). Additionally, these triggers are prosodically disadvantaged because unstressed syllables are generally less prominent, having lower amplitude and lacking salient pitch contours than stressed syllables. In Italian in particular, vowels in unstressed syllables have been found to be shorter than their stressed vowel counterparts (D'Imperio and Rosenthall 1999). Walker suggests that height harmony systems improve the perceptibility of the feature [high] by extending that feature to a prosodically prominent position, the stressed syllable, where it will be associated with a vowel of increased duration and amplitude. According to Walker, the asymmetries present in height harmony systems (only high vowels can trigger harmony, and harmony propagates only to the stressed syllable) may be explained as a consequence of the need for perceptual enhancement of a weak cue.

3. Previous Accounts

Transparency and opacity have provided persistent challenges to phonological theory. A fundamental understanding of these phenomena implicates long-standing phonological issues: the range of possible rules or constraints, the nature of representations, the key issue of locality, markedness and the phonetic bases of phonological patterning. In this section, we review various analyses of transparency and opacity. Our aim is to highlight the central issues and the key insights, and to point out the areas where improvements can be expected.

The first generative account of vowel harmony is considered to be Lightner's (1965) who promoted the intuition that stems in vowel harmony languages are arbitrarily marked for a value of the feature exhibiting harmony. In this 'root-marker' approach, the Akan stem for 'pierce' [fiti] would be marked for the feature [+ATR] and the stem for 'show' [cɪrɛ] would be marked for [–ATR] (data from the Asante dialect of Akan, Clements 1981). This feature is then realized on all vowels of the stem and on harmonizing affixes that may appear in combination with the stem. Representative derivations of *o-fiti-i* 'he pierced it' and *ɔ-cɪrɛ-ɪ* 'he showed it' are in (12). The intuition that the harmonizing feature is a property of the stem or, more precisely, that it is not a property of any particular segment in the stem invited attempts to treat vowel harmony in ways parallel to contemporary proposals on the treatment of tonal phenomena (Goldsmith 1976). In the domain of tone and around the same time in the development of phonological theory, substantial attention was devoted to data where tonal melodies on a tier independent from that of the segmental sequence are associated to the segmental sequence via general principles of association. Spreading, specifically, was the operation that adds association lines between, say, a single low or 'L' tonal specification and each vowel in the stem. The same formal mechanism of spreading could then be applied to vowel harmony (Clements 1976). The main intuition of the 'root-marker' approach, feature sharing among multiple vowels in stems or in stem plus affix combinations, could thus be expressed as the direct result of this independently motivated formal mechanism of spreading.

(12) Analysis of ATR harmony in Akan

a. o-fiti-i → o - f i t i - i   b. ɔ-cɪrɛ-ɪ → ɔ - c ɪ r ɛ - ɪ

[+ATR] [+ATR] [–ATR] [–ATR]

An immediate consequence of pursuing such an approach to vowel harmony is that the behavior of opaque vowels seems to follow from independently motivated constraints on autosegmental representations. For instance, in Clements (1976, 1980, 1985) opaque vowels are specified with their values for the harmonic feature, so that such a pre-existing association on an opaque vowel blocks spreading from the stem beyond the opaque vowel. The blocking is due to the well-known constraint against crossing association lines. To make this concrete, recall that in Wolof /a/ is in some cases opaque to [ATR] harmony and, in those cases, the vowel surfaces as [–ATR]. For instance, when the suffix [kat] intervenes between a stem and another suffix, it blocks harmony from a [+ATR] stem to the following suffix. In (13), we show how this fact follows from autosegmental principles. The feature specification of the stem vowel cannot spread to the suffix, as shown by the dotted line in (13)a, because it would result in line crossing; ‘A’ denotes a low vowel unspecified for the value of [ATR]. The unique allowable result is (13)b, where the [–ATR] specification of [kat] spreads to the following suffix. In different words, opacity is seen here as a reflex of the fundamental phonological principle of locality. The final suffix receives its featural specification from its closest eligible donor, its preceding vowel, not from the first stem vowel which is farther away.

(13) a. fóót-kat-Am   b. fóót-kat-am

[+ATR][–ATR]   [+ATR][–ATR]

Rule-based accounts of transparency either write in the rule the optional transparent material that can intervene between trigger and target (Ringen 1975: 24) or apply the rule of vowel harmony to all vowels in the stem. In the latter case, the representations are then adjusted so that transparent vowels end up with the expected values for the harmonizing feature (via neutralization rules, as in Vago 1980).

Unlike opacity, transparency has proved to be a recalcitrant problem for phonologists throughout the past approximately fifty-year period of theoretical developments. In autosegmental approaches, the behavior of transparent vowels was not as directly derivable from general principles of representations as was the case with opaque vowels. Consider, for example, the Hungarian diminutives of the proper names Erzsébet and Klára, Erzsi [ers-i] and Klári [klɑːr-i]. When the diminutives are further combined with the endearment suffix [–kɔ/–kɛ], the result is [ersikɛ] vs. [klɑːr-i-kɔ]. How is the backness of the suffix transmitted to the suffix vowel? Clements (1977) proposes that, in a first step, the feature [+back] spreads to all vowels of the stem-suffix-suffix combination including the medial [i]. This step expresses the intuition, by means of spreading, that the suffix is back because the stem vowel is back. But it also results in a representation where [+back] is linked to the medial high, unround vowel. Hungarian lacks such unround, nonlow, back vowels. In Clements’ (1977) analysis, then, this intermediate representation is corrected by linking [–back] to that vowel. This latter step is conceptually equivalent to the absolute neutralization rules of rule-based analyses, as in Vago (1976, 1980). Its technical implementation in autosegmental accounts, however, effectively deconstructs the result of the first spreading step to a representation where each vowel has its own separate specification of backness (Anderson 1980, in a critique of such approaches to vowel harmony, calls this the 'mitosis' step; Kenstowicz 1994 brings out independent issues with such manipulations on autosegmental representations). Kiparsky (1981), Clements & Sezer (1982) and Ringen (1988) proposed variants of this basic analysis which proceed to either parameterize the harmonic feature bearing units or keeping the features at a different plane from that in which vowel harmony applies (or keeping the features at a different tier as in those accounts that hold the relevant featural specifications of transparent vowels 'locked in' the so-called segmental core). The effect of such elaborations is that in languages with transparent vowels the spreading envisioned in the first step of Clements' (1977) analysis above would not link to these vowels at all. The 'correction' step could thus be avoided. Representative works pursuing this perspective are Kiparsky 1981, Goldsmith 1985, Steriade 1987 and Ringen 1988; for a critical review see Kenstowicz 1994, pp. 357-9, Farkas & Beddor 1987 and Steriade 1995, pp. 135 ff.).

The issue of transparent vowels first participating in harmony and then being readjusted in some way persists across different phonological theories, including those that adopt non-derivational theoretical frameworks. Thus, in Ringen & Vago's (1998) Optimality Theory analysis of Hungarian, both the representations and the constraints encode a distinction between transparent and all other vowels. On the side of representations, the transparent vowel in e.g. [klɑːr-i-ka] is assumed to be unspecified for backness. In Ringen & Vago's (1998) analysis, this assumption crucially enters into the evaluation of the constraint ensuring that the harmonizing feature links throughout every vowel in the word. That constraint is defined so as it is not violated by the presence of a transparent vowel placed between two back vowels (e.g. see tableau (12) in Ringen & Vago 1998). On the side of the constraints, the distinction between transparent and non-transparent vowel is encoded in the constraint set used in Ringen & Vago (1998) (e.g. see the definition of their constraint in (5b)). NíChiosáin & Padgett (2001) and Baković and Wilson (2000) are two later approaches illustrating the same issue. The technical details among the different accounts are of course rather different. But, all along, the problem of transparency has remained a persistent challenge.

In early Optimality Theory (Prince and Smolensky 1993) accounts of vowel harmony, the key notion of spreading is inherited from autosegmental. The formal implementation of spreading pursued an extension of the constraint schema known as ALIGN (McCarthy and Prince 1993). ALIGN constraints were originally used for aligning morpheme edges with prosodic domain edges. For feature spreading, as in vowel harmony, the alignment constraints require the alignment of harmonizing features with selected edges of domains. Apart from this, however, within the scope of early Optimality Theory (Prince and Smolensky 1993) applications, attempts to address the transparency challenge are less reliant on representational assumptions. Thus, Smolensky (1993) in his treatment of transparency in Finnish harmony proposes that the reason for the transparency of [i] is that the feature combination that would result with imposing [+back] on [i] is marked -- his constraint *[+B/I]. This constraint is ranked higher than *EMBEDDED, which penalizes embedded feature domains. Then, if ALIGN[+back] is ranked higher than the constraint against *EMBEDDED domains, this would result in transparency (the other ranking results in opacity; see Kirchner (1993), Akinlabi (1994), Pulleyblank (1994), Cole and Kisseberth (1995), Ringen & Vago (1998) for related analyses and discussion). This solution, then, excludes transparent vowels from the domain harmony. But because these vowels intervene between two vowels which agree in terms of the harmonizing feature, this analysis forces the conclusion that harmony can be non-local, an unwelcome position on both formal theoretical and typological grounds (McCarthy 1989, Clements and Hume 1995, Gafos 1999, NíChiosáin & Padgett 2001). Subsequent accounts of vowel harmony in Optimality Theory, discussed below, make efforts to maintain locality in vowel harmony while accounting for opacity and transparency.

In one such account, Kiparsky and Pajusalu (2003) construct a typology of vowel harmony, with a special focus on neutral vowels. In the Kiparsky and Pajusalu's system, the presence of vowel harmony is a consequence of a high ranked constraint AGREE(F), where F is the harmonizing feature; thus, AGREE(ATR) for 'tongue root' vowel harmony languages or AGREE(BACK) for 'palatal' vowel harmony languages and so on. The constraint is formulated in (14) in a way that maintains strict locality – evaluating a candidate with respect to this constraint never requires comparing segments that are not adjacent in the articulatory domain (Baković 2000:4, Gafos 1999).

(14) AGREE(BK)

Articulatorily adjacent vowels must have the same specification for the feature [back].

In addition to AGREE constraints, the Kiparsky & Pajusalu system works with two more types of constraints: markedness constraints such as "front vowels must be nonlow and unrounded (*ä, *ö, *ü)" which oppose harmony, and positional faithfulness constraints such as IDENT-FOOT$_1$ and IDENT-STEM. Kiparsky & Pajusalu (2003) use the latter constraints to account for "derived environment" asymmetries in harmonic patterning. Specifically, such domain-specific constraints can capture the pattern that harmony may be stricter in derived environments than within a morpheme and stricter in non-initial feet than in the more salient and thus phonologically privileged initial foot. This is formally implemented using the concept of constraint conjunction. In OT, Smolensky (1993, 1995, 1997) has argued that two constraint violations are worse when they occur locally than when they occur non-locally. This idea appears to be useful in capturing patterns of optimization in a wide range of cases (see Smolensky 1993, 1995, 1997, on segmental markedness, sonority profiles, and vowel harmony, respectively; Itô and Mester 1997, Alderete 1997 on dissimilation, Gafos and Lombardi 1999 on consonant transparency, among others). To express this property of constraint violation, Smolensky proposed that the constraint component of OT includes "an operation in UG by which two constraints governing substructures of a given local domain are conjoined into a higher ranked constraint" (Smolensky 1993). This operation, called Local Conjunction, is defined as shown below.

(15) The Local Conjunction of $\mathbb{C}_1$ and $\mathbb{C}_2$ in domain D

$\mathbb{C}_1 \&_l \mathbb{C}_2$, is violated when there is some domain of type D in which both $\mathbb{C}_1$ and $\mathbb{C}_2$ are violated. Universally, $\mathbb{C}_1 \&_l \mathbb{C}_2 >> \mathbb{C}_1, \mathbb{C}_2$.

One use of constraint conjunction in the Kiparsky & Pajusalu (2003) system concerns patterns of stem-internal harmony. Thus, in Finnish, front and back vowels contrast in the second syllable of a stem, sinä 'you' vs. kina 'squable', riittä 'suffice' vs. viitta 'cloak'. But beyond the first foot, this potential for contrast disappears, kipinä 'spark', *kipina. Furthemore, in morphologically complex contexts or 'derived environments' such as stem-suffix combinations, the harmonic forces are stronger than within stems: thus, viit-tä 'five-ABESSIVE', *viit-ta. To account for this patterning, a conjoined constraint made out of the individual IDENT-F$_1$(BK) and IDENT-STEM(BK) constraints is employed.

(16) Locally conjoined constraint

IDENT-FOOT$_1$(BK) & IDENT-STEM(BK): an [α BK] input segment in the *first foot* of a *stem* cannot have a [–α BK] output correspondent.

As a consequence of this constraint, AGREE violations are allowed within morphological or prosodically privileged domains such as the stem or the first foot. In (17), this is formally expressed by the ranking IDENT-FOOT$_1$(BK) & IDENT-STEM(BK) >> AGREE(BK).

(17) Agreement violations admitted within the privileged domain of the stem/ first foot

	IDENT-FOOT$_1$(BK) & IDENT-STEM(BK)	AGREE(BK)
([viita])$_{Ft}$		*
([viitä])$_{Ft}$	*!	

Since stems impose their backness value as in viit-tä 'five-ABESSIVE', we must also posit the ranking AGREE(BK) >> *ä, *ö, *ü. For viit-tä 'five-ABESSIVE', the conjoined constraint is silent since the suffix vowel is foot-initial but not stem-internal. But in Uyghur, when the neutral vowel is the only vowel in the stem, the suffix is back: [i] – a, *[i] – ä. This difference between Finnish versus Uyghur in the way sole transparent vowels combine with suffixes is strikingly simple and Kiparsky & Pajusalu (2003) propose a formal analysis that seems correct. In Finnish, the ranking is AGREE(BK) >> *ä, resulting in transparent vowels imposing their frontness on suffixes despite the markedness of low front vowels: [i ä], *[i a]. In Uyghur, *ä >> AGREE(BK), resulting in transparent vowels failing to impose their frontness on suffixes: *[i ä], [i a].

When in the context following a back vowel, however, Finnish and Uyghur exhibit the same pattern, namely, [a i a], *[a i ä]. This is the case of transparency to which we turn next. To account for transparency, Kiparsky & Pajusalu (2003) build parsimoniously on the ideas used in capturing the stem-internal vs. derived environment effects described above. As discussed, stem-internally in Finnish, some disharmony is allowed as seen with [i a] sequences. However, [ä a] sequences are not permitted. The key insight here from Kiparsky & Pajusalu (2003) is that harmony violations with marked vowels are avoided or in other words "disharmony with marked vowels is both worse than disharmony alone, and worse than markedness alone" (Kiparsky & Pajusalu 2003:8). Formally, this insight enters the grammar as another locally conjoined constraint shown in (18). As a direct effect of this constraint, *[a ä] is excluded because [ä] is marked and the sequence is disharmonic, but [i a] is admitted because the sequence is disharmonic but none of the vowels is marked.

(18) Generalized Marked Harmony: AGREE(BK) & *ä, *ö, *ü

This key intuition, capturing such facts about stem-internal harmonic patterning, can be extended to account for transparency. Specifically, the ranking Generalized Marked Harmony >> AGREE(BK) results in transparency. Given /a i – ä/ as input and comparing candidates [a i – ä] and [a i – a], the former candidate incurs a violation of Generalized Marked Harmony: the first two vowels in this string disagree in terms of the harmonic feature and the last vowel is marked with respect to that feature. The other candidate, [a i – a], does not violate Generalized Marked Harmony because it does not contain a marked vowel, though it does incur two violations of AGREE(BK).[6] This is the ranking accounting for the case of transparency in Finnish and Uyghur.

[6] This use of constraint conjunction does away with the domain specification in the original definition of conjoined constraints, see (15), in that evaluation of the conjoined constraint pools violations of the individual constraints irrespective of their locus in the form being evaluated; hence, the 'generalized' in the constraint reference.

(19) Transparency

/a i - ä/	AGREE(BK) & *ä, *ö, *ü	AGREE(BK)
i. [a i – ä]	*!	*
ii. ☞ [a i – a]		**

In this approach, then, the backness of the suffix vowel is related to the backness of the first stem vowel in an indirect and interesting way. The reason why markedness in the suffix is a decisive factor is because the first two vowels, [a i], disagree. Since the second vowel is a neutral vowel (hence, front), disagreement implies that the first vowel must be back. Constraint conjunction imposes in this indirect way the same value of backness between the first and the third vowel.

Flipping the ranking of the constraints needed to get transparency results in opacity. That is, with the opposite ranking, AGREE(BK) >> AGREE(BK) & *ä, *ö, *ü, and for input /a i – ä/, AGREE(BK) decides in favor of the opaque candidate [a i – ä]. This is the pattern observed, for example, in Eastern Khanty. However, note that in the ranking necessary to express opacity, AGREE(BK) >> AGREE(BK) & *ä, *ö, *ü, the conjoined constraint is outranked by one of its constituent constraints. This is generally ruled out in OT (see Kager 1999: 393).

(20) Opacity

/a i - ä/	AGREE(BK)	AGREE(BK) & *ä, *ö, *ü
i. ☞ [a i – ä]	*	*
ii. [a i – a]	**!	

It is a notable corollary of the Kiparsky & Pajusalu (2003) system that back vowels in ‘palatal’ harmony languages are opaque rather than transparent. That is, in the system entertained here, [ä o ä] is harmonically bound by [ä o a]. The sequence [ä o a] violates Generalized Marked Harmony once and AGREE(BK) once. The sequence [ä o ä] violates Generalized Marked Harmony twice and AGREE(BK) twice. Thus, regardless of the ranking between the two constraints, Generalized Marked Harmony and AGREE(BK), [ä o ä] < [ä o a]. This is a remarkable result, following from two ‘first principles’ in the Kiparsky & Pajusalu system, markedness and agreement.

We now return to the Hungarian facts to work out the implications of transparency and opacity being present in the same system. To account for transparency, we must posit the ranking AGREE(BK) & *e >> AGREE(BK) (henceforth, when referring to Hungarian forms, the symbol for the low front vowel will be ‘e’ in place of Kiparsky & Pajusalu’s ‘ä’ symbol). Candidate ((21).ii) [[a i] e], violates the conjoined constraint AGREE(BK) & *e because ‘e’ is marked for the harmonizing feature (BK) and [i] is disharmonic for BK. This entails the desired harmonic ordering, that is, [a i e] (opacity) < [a i a] (transparency).

(21) AGREE(BK) & *e, *ö, *ü >> AGREE(BK)

	AGREE(BK) & *e	AGREE(BK)
i. ☞ [[a i] a]		**
ii. [[a i] e]	*!	*

In this formal system, then, markedness as embodied by the *e constraint plays a crucial role in deriving transparency. However, Hungarian presents a problem here. The vowel é [e:] is a mid a vowel, whereas e is a low or at least lower vowel, typically transcribed as [ɛ] (Siptár & Törkenczy

2000, pp. 385, 426). This is the standard phonological classification. Furthermore, ultrasound imaging data show a rather clear difference in tongue height between the group [iː i eː] and [ɛ] – see (27). The latter vowel shows a much lower and retracted tongue body posture than the other vowels. In Hungarian, there are suffixes with front non-low surface alternants such as the Adessive suffix which alternates between [-neːl], [-naːl]. The markedness constraint "front vowels must be nonlow and unrounded (*e, *ö, *ü)" is not violated by the vowel in [-neːl]. The conjoined constraint Generalized Marked Harmony is therefore also not violated in [[a i] eː] sequences and the decision is made by the other constraint AGREE(BK) which declares [[a i] eː] > [[a i] aː]. This is the wrong outcome. In Hungarian, the choice between [-neːl], [-naːl] is made in the same way as for other suffixes such as the Dative [-nɛk], [-nɔk].

Furthermore, unlike Finnish and Turkish, Hungarian admits disharmonic or mixed stems with marked vowels such as [fotel] 'armchair' and [farmer] 'jeans' though some support can be given to the view that these are recent loans (Kertész 2003: 67). In Finnish recall that [a ä] stems are not permitted but [a i] stems are, and in Turkish [o ü] sequences are not permitted but [o e] are. Hungarian does have back-initial stems followed by front round vowels as in sofőr 'driver', parfüm 'perfume' and kosztüm 'costume'. These words are relatively recent loans (Kertész 2003: 67), perhaps belonging to a lexical 'periphery' in the sense of Itô and Mester (1995). But in terms of their harmonic behavior they are regular. They are followed by front suffixes in agreement with the frontness of the last stem vowel. To account for the opacity pattern exhibited in these stems, the ranking scheme must be AGREE(BK) >> Generalized Marked Harmony. But recall that the transparency pattern required the ranking Generalized Marked Harmony >> AGREE(BK). The relevant datum is sequences of the [[a y] e] profile, the opaque candidate, versus [[a y] a], the transparent candidate. The crucial decision rests on how AGREE(BK) & *e, *ö, *ü is evaluated. In [[a y] e], [a y] disagree and e is marked. This is the same profile of violations for the transparent winner [[a i] a] discussed above, and implies at least one violation of AGREE(BK) & *e, *ö, *ü. Furthermore, the subsequence [a y] may also be considered to violate AGREE(BK) & *e, *ö, *ü exactly as it was assumed for the stem-internal [ä a] sequences in Finnish above: [a y] disagree and [y] is marked. If two violations of AGREE(BK) & *e, *ö, *ü are assigned, then [[a y] a] is the predicted winner. If only one violation of AGREE(BK) & *e, *ö, *ü is assigned, then [[a y] e] is the correctly predicted winner.

(22) AGREE(BK) & *e, *ö, *ü >> AGREE(BK)

	AGREE(BK) & *e	AGREE(BK)
i. [[a y] a]	*	**
ii. [[a y] e]	* (*?)	*

In this system, it is conceivable to split the conjoined constraint into two separate ones, AGREE(BK) & *e and AGREE(BK) & *y. This permits more freedom in differentially weighing violations of the corresponding constraints as shown in (23). But in this case, this change does not help, since to account for transparency we must posit AGREE(BK) & *e as the highest ranked constraint. This constraint is violated by the attested candidate [[a y] e] output which is thus predicted to be suboptimal.

(23) Splitting the conjoined constraint: AGREE(BK) & *e >> AGREE(BK) >> AGREE(BK) & *y

	AGREE(BK) & *e	AGREE(BK)	AGREE(BK) & *y
i. ☞ [[a y] a]		**	*
ii. [[a y] e]	*!	*	*

In sum, the Hungarian facts pose certain challenges for the Kiparsky & Pajusalu (2003) system, especially with the proposed account for opacity. That account relies on the use of conjoined constraints. Such constraints, both in their original proposal (Smolensky 1993) and subsequent uses (Kager 1999: 393), are assumed to outrank the individual constraints from which they are constructed. This theoretical restriction must be given up in the formal system that achieves opacity in Kiparsky & Pajusalu's (2003) typological account. At the same time, the Kiparsky & Pajusalu system is notable in curving out a prominent role for markedness considerations in harmony and in the continuity in the formal treatment of harmonic behavior it establishes between stem-internal and derived environments.

Another account for transparency in vowel harmony is set forth in Baković and Wilson (2000). This account makes crucial use of a particular species of constraints, called *targeted constraints* originally proposed in Wilson (2000). Targeted constraints integrate perceptual and articulatory information in their definition (inspired by the Licensing-by-Cue framework in Jun 1995 and Steriade 1997, 2000). For Wolof ATR harmony, one of Baković and Wilson's test cases, the phonetic basis for their targeted constraint is the articulatory and acoustic antagonism between [+high] and [–ATR]. Recall from section 2 that raising the tongue body for a high vowel, which lowers F1, is antagonistic to tongue root retraction for a [–ATR] vowel, which raises F1. The targeted constraint in (24)a incorporates this markedness, banning [+high, –ATR] vowels. Targeted constraints differ from standard markedness constraints in that, in addition to disallowing certain marked structures, they also point to specific 'repairs' for these structures. In (24)a, [+high, –ATR] vowels are to be 'repaired' by replacing them with unmarked vowels which are adjacent to their marked correspondents on an acoustic similarity scale 'F1-Sim'. The F1-Sim scale, defined in (24)b, arranges vowels according to their F1 values, from low (left) to high (right). Because in that scale the marked [+high, –ATR] vowel [ɪ] is adjacent to [i], the targeted constraint repairs *[tɛkkɪ - lɛɛn] by replacing the marked [ɪ] with [i], thus giving the actual Wolof output [tɛkki - lɛɛn].[7] The reader will note the resemblance of this intuition to the standard autosegmental analysis of transparency we reviewed earlier. Putting aside details of how this intuition is implemented in Optimality Theory, the effect is that the targeted constraint works in favor of transparency in cases where full harmony as in *[tɛkkɪ - lɛɛn] would produce a marked vowel such as [ɪ]. The output [tɛkki - lɛɛn], with the transparent [i], is the closest form to the fully harmonic *[tɛkkɪ - lɛɛn].

(24) Baković and Wilson's 'targeted' constraint in the context of 'tongue root' harmony

a. →NO(+HI, –ATR): x' > x iff x' is exactly like x except that at least one target vowel α has been replaced by a member of F1-Sim(α) that is not marked according to HI, ATR.

[7] We assume that such substitutions respect vowel height identity. Thus, even though [e] may be closer to [ɪ] than [i] is, it is the latter vowel which is chosen as a replacement for [ɪ]. See our earlier discussion of the acoustic similarity between [ɪ] and [e].

b. F1-Sim: Vowels that occupy the same level or adjacent levels on one of the following scales are non-distinct.

(lower F1) i < ɪ, e < ɛ < æ (higher F1)

u < ʊ, o < ɔ < a

In order to account for opacity, Baković and Wilson propose a double-sided agreement constraint, AGREE(F//), which is violated when a vowel between two [αF] vowels is [−αF]. This kind of constraint always prefers opaque or fully harmonic candidates to transparent ones. In a language like Yoruba, where the high vowels /i, u/ are opaque to harmony, the relevant constraints are ranked as in (25)a. In Wolof, where the same vowels /i, u/ are transparent to harmony, the constraints are ranked as in (25)b.

(25) a. →NO(+HI, –ATR) » AGREE(ATR//) » AGREE(ATR)

b. →NO(+HI, –ATR) » AGREE(ATR) » AGREE(ATR//)

Baković and Wilson's analysis thus correctly derives the facts of transparency and opacity in certain 'tongue root' harmony systems. However, the analysis encounters difficulties in other vowel harmony systems. As can be seen in (25), two different constraint rankings are required to obtain transparency versus opacity for a particular set of vowels. If we maintain, following the standard OT assumptions, that a single constraint ranking holds within a given language, then it is not possible to require that constraint A outranks constraint B in some cases in that language, while constraint B outranks constraint A in other cases in the same language. Because the rankings in (25)a and (25)b refer to different languages, different rankings are to be expected. The problem arises when one considers a single language in which the set of vowels singled out by the targeted constraint does not behave uniformly under vowel harmony. This is the case in Hungarian.

In Hungarian, the phonetic basis for a targeted constraint would likely be F2, which is largely modulated by backness, with front vowels characterized by high F2 values and back vowels with low F2 values. Inspired by Baković and Wilson's approach, we attempt a formulation of the relevant targeted constraint in (26). Because rounding enhances lowering of F2, [+back, +round] vowels have a perceptually-desirable very low F2, and [+back, –round] vowels, which have somewhat higher F2 values, are perceptually less desirable. Thus, marked [+back, –round] vowels would be replaced by an unmarked member of a similarity scale like F2-Sim, according to the targeted constraint →NO(+BK, –RD).

(26) A constraint to capture Hungarian transparency in Baković and Wilson's system

a. →NO(+BK, –RD): x' is preferred over x (x' > x) iff x' is exactly like x except that at least one target vowel α has been replaced by a member of F2-Sim what is not marked according to BK, RD.

b. F2-Sim: Vowels that occupy the same level or adjacent levels on one of the following scales are non-distinct:

(higher F2) i, e, ɛ < ɯ, ɤ, a (lower F2)

y, ø < u, o

The targeted constraint →NO(+BK, –RD) in (26)a can be used to account for the facts of transparency in Hungarian, as it establishes a preference for a form with a transparent vowel, like [papiːr-nɔk], over a fully-assimilated form like [papɯːr-nɔk]. →NO(+BK, –RD), however, has nothing to say for cases of opacity in Hungarian, because no possible candidate (forms like the fully-assimilated [parfum-nɔk], transparent [parfym-nɔk], opaque [parfym-nɛk]) violates this constraint -- none of these candidates contains a marked vowel. Because →NO(+BK, –RD) does not exert a preference, the choice of candidates is left to a lower-ranked AGREE constraint which prefers a fully harmonic candidate, [parfum-nɔk], over the opaque candidate.[8] Consequently, no single ranking of the targeted constraint, faithfulness constraint, and the relevant AGREE constraints accounts for the facts of palatal harmony in Hungarian.

The challenges reviewed so far stem from the need to reorganize the grammar forces resulting in transparency to get opacity. This recourse to different rankings for transparency and opacity is shared by two approaches discussed above. There is no hard evidence *a priori* that this must be true of any system that aims at capturing both transparency and opacity. After all, focusing on palatal vowel harmony systems and without loss of generalization, within any given language, the transparent vowel is different from the opaque vowel, e.g. [i] is transparent and [y] is opaque in Hungarian/Finnish. An alternative account of transparency and opacity could capitalize on inherent properties of the vowels in question while leaving the general schema of grammatical forces the same.

The need for different grammar rankings for transparency and opacity, shared by the two approaches discussed above, can be traced to a crucial assumption. That assumption is that transparent vowels categorically do not partake in agreement, as required by harmony. In other words, (all) transparent vowels categorically disagree with their adjacent vowels. A diametrically opposed perspective is to abandon this key assumption of disagreement and devise a system admitting differential agreement relations between vowels — that is, not simply agree versus disagree but a spectrum of agreement qualities tailored to the specific combination of vowels involved in the relation for which agreement is assessed. Benus (2005) develops a version of this approach based on a rigorous experimental study of Hungarian transparent vowels. The general schema governing both transparency and opacity in Benus's account is expressed by a single ranking: PERCEPTUAL FAITHFULNESS >> AGREEMENT >> ARTICULATORY FAITHFULNESS. The broad correspondence between the constraints in this ranking and those discussed so far is as follows. AGREEMENT corresponds to AGREE(BK), requiring overlapping vowels to agree as much as possible in constriction location. Its opposing but lower ranked constraint is ARTICULATORY FAITHFULNESS. This corresponds to IDENT(BK) of previous accounts. The ranking AGREEMENT >> ARTICULATORY FAITHFULNESS expresses the simple fact that the language exhibits vowel harmony. The dominating PERCEPTUAL FAITHFULNESS tames the harmonic agreement forces to degrees of agreement that leave the perceptual identity of the vowels in question unchanged. The closest parallel to PERCEPTUAL FAITHFULNESS in the previously reviewed accounts is Baković & Wilson's (2000) similarity scale – in that analysis, transparent vowels are by-products of an optimization starting with the full assimilation candidate and changing that to a less marked candidate while maintaining similarity with the full assimilation candidate. Overall, then, the main idea in Benus' proposal is

[8] Adding a high-ranked faithfulness constraint like IDENT-STEM(BK) (a positional faithfulness constraint (Beckman 1998) which prefers faithfulness within the root) solves the problem for opaque vowels. IDENT-STEM(BK) would be violated by the fully-assimilated candidate, and the opaque candidate would win because it violates only the low-ranked agree constraint. However, such a solution makes incorrect predictions for cases of transparency: the ranking →NO(+BK, –RD) » IDENT-STEM(BK) » AGREE prefers the opaque candidate.

that vowel harmony is driven by articulatory agreement between overlapping vowel gestures and that this agreement is constrained perceptually. In an A-I sequence, where ‘A’ represents any back vowel and ‘I’ any front vowel, vowels differ with respect to their potential for agreement: following any given back vowel, a high front vowel like /í/ is most retractable, a mid front vowel like /e/ is somewhat retractable, and the high front round /y/ is minimally retractable. Articulatory-perceptual quantal relations are crucial in determining the degree to which a vowel can be retracted without losing its perceptual identity. For transparent vowels, such as the [i] in the sequence [a i – V^{suffix}], articulatory agreement with the preceding back vowel can be substantial without changing the perceptual identity of the [i]. In turn, the degree of articulatory backing induced on the transparent vowel by agreement with its preceding back vowel is sufficient to trigger a back suffix, hence [a i – a]. For opaque vowels, the ranking of constraints remains the same. The difference in behavior between opaque and transparent emerges from the quantal charateristics of the different vowels. In [a y – V^{suffix}], the front round vowel cannot be retracted to the same degree as the vowel [i] without losing its perceptual identity of being a front vowel. The limited potential of agreement with a back vowel for [y] results in less articulatory backing on the [y] which in turn results in the selection of a front suffix, hence [a y – e]. In other words, the high ranking of PERCEPTUAL FAITHFULNESS prevents establishing articulatory agreement to a degree that would induce a back suffix alternant just when the front vowel is [y].

The typological implications of the phonetically-informed approach pursued in Benus (2005) have yet to be pursued systematically. That approach crucially relies on rigorous phonetic records. There is a great disparity between the range of languages whose vowel harmony patterns have been described and even analyzed in the theoretical literature and those for which we have systematical phonetic investigations for the same or even a subset of the same data. Apart from Benus’ studies on Hungarian and some more recent data on transparency from Kinande to be discussed in the next section, there are no other studies we are aware of that have examined systematically transparency and opacity patterns in vowel harmony using rigorous experimental methods. It would not be an exaggeration to state that we have only recently begun to register the phonetic record for transparency and opacity using rigorous methods.

Thus, two key insights have emerged. In the typological study of Kiparsky & Pajusalu (2003), markedness and its prioritazation with other generally accepted grammar principles such as AGREE go a long way in capturing essential distinctions between the different languages reviewed in that study. The other idea from Baković & Wilson’s (2000) theoretical contribution and Benus’ (2005) experimentally-based work is that considerations of the relation between articulation and acoustics play a crucial role in transparency and opacity. It seems that a combination of the two insights, supported through parallel pursuit of theoretical and experimental work, would provide a solid basis for informing phonological theory in two essential domains: the nature of the constraints as well as the ways in which the relative contribution of these constraints captures cross-linguistic variation.

4. Phonetic Bases

Understanding the phonetic bases of opacity and transparency must begin with an understanding of the phonetic bases of vowel harmony in general. Since Gay (1977, 1978) it is known that a non-contiguous sequence of identical vowels such as u-u in “kutup” is produced by speakers of English with a discontinuity both in the articulatory and the electromyographic measures of lip rounding (see also Boyce 1988, 1990). For example, in the electromyographic signal there is a trough coincident with the production of the intervening consonant. The cessation of muscle activity during the consonant is consistent with the hypothesis that the linguistic representation underlying the production of lip rounding schedules the rounding of the two identical vowels as two independent events, $[u]^{Round}C[u]^{Round}$ (C is a variable for any permissible intervocalic consonant or consonant cluster). A number of other studies have documented the same trough pattern in the production of non-contiguous identical vowels in Spanish, French (Perkell 1986) and Swedish (McAllister 1978, Engstrand 1981). In contrast to these cases, Boyce (1988, 1990) found in Turkish a plateau of continuous activity for /uCu/ utterances both in muscle excitation patterns (of the orbicularic oris) and in lower lip protrusion kinematics. This pattern of results, the English trough versus the Turkish plateau, seems to reflect the fact that Turkish but not English has vowel (rounding) harmony. Furthermore, the linguistic representation underlying the production of lip rounding in Turkish is consistent with a central idea of autosegmental theory, namely, that assimilation and harmony involve representations in which a single instance of the assimilating or harmonizing property extends over a domain encompassing all segments required to agree on that property. Thus, in Turkish, the rounding property of the two vowels would extend over a domain encompassing both vowels in /uCu/ (Clements 1977, Kiparsky 1981, Goldsmith 1985) and this is what gives rise to the plateau seen in Boyce's study.

The picture becomes more complex when we consider the facts of transparency. As we have seen, many languages with harmony include vowels that can intervene between the trigger and the target of vowel harmony even when they bear the opposite value for the harmonizing feature. In Hungarian, *papír* selects [+back] suffixes, such as *nak* 'DATIVE', *ház* 'ALLATIVE', *tól* 'ABLATIVE', *ban* 'INESSIVE' in agreement with the [+back] value of the initial stem vowel and despite the intervening [–back] value of /í/. At the heart of the problem that transparent vowels pose for the phonetic basis of vowel harmony is an assumption about their representation. The assumption is that the phonological category of a transparent vowel is invariant across different contexts and irrelevant to the quality of the suffix following the transparent vowel. In an impressionistic sense, the transparent vowels in words like *bul**i**-nak* 'party-DATIVE', *h**í**d-nak* 'bridge-DATIVE' or *mam**i**cs**i**-nak* 'mother-DIMINUTIVE-DATIVE' are not perceptually different from those in *bil**i**-nek* 'pot-DATIVE' or *v**í**z-nek* 'water-DATIVE'. Hence, they are assumed to be invariant across these different contexts. However, it is well-known that for vowels a relatively stable acoustic output can be produced using multiple articulatory strategies and constriction locations. Stevens (1972, 1989) promotes the idea that the relation between acoustic and articulatory dimensions of phonetic form displays discontinuous characteristics. In 'stable' regions of an abstract 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 articulatory-acoustic 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.

A group of sounds with well-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 [i] may be articulatorily retracted to some degree without losing its perceptual identity. The central result is illustrated in Figure 2 below. 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.

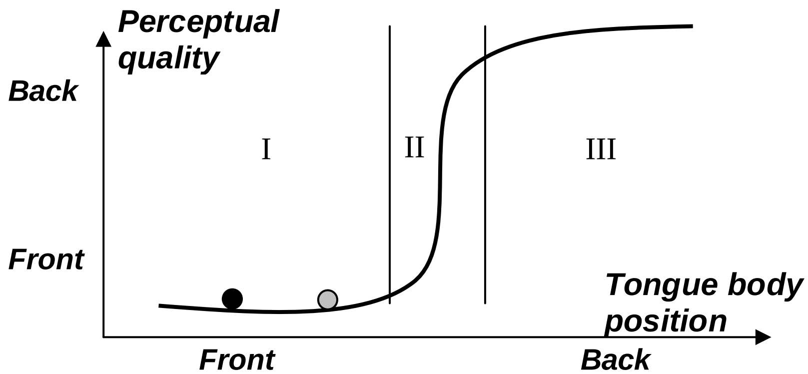


Figure 2. Non-linearity in front non-low unround vowels. Tongue body retraction is shown as the difference between the x-coordinates of the two balls, while the minimal perceptual effect of this retraction is shown on the y-axis.

We stress that the foundational results of Stevens and Wood above are not about a specific 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.

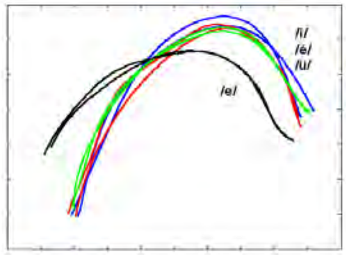
This hypothesis has been pursued in studies of Hungarian transparent vowels [i:], [i] and [e:] using a combination of Electromagnetic Articulometry and Ultrasound (Gafos & Benus 2003, Benus, Gafos & Goldstein 2004, Benus 2005, Benus & Gafos 2007). In these studies, one set of stimuli consisted of word pairs where transparent vowels occur in stems triggering front or back suffixes. In the first set, all words were trisyllabic, e.g. *zefír-ben* 'zephyr-INESSIVE' vs. *zafír-ban* 'sapphire-INESSIVE'. Such pairs permitted comparisons of the tongue posture for /í/ in the two vowel harmony contexts, front and back. The second set of stimuli consisted of monosyllabic words. For example, /é/ in *szél* 'wind' was compared to /é/ in *cél* 'aim'. The forms *szél*, *cél* correspond to the Nominative case of the respective nouns, where there is no overt suffix. When these stems appear with overt suffixes, *szél* triggers a front while *cél* triggers a back suffix: *szél-nek* 'wind-DATIVE' vs. *cél-nak* 'aim-DATIVE'. Once again, such pairs permit comparisons of the tongue posture for /é/ in the two vowel harmony contexts, front and back. However, they differ from pairs like *zefír* vs. *zafír* in one crucial respect. For *zefír* vs. *zafír*, the difference in suffix choice, front for *zefír* vs. back for *zafír*, is typically ascribed to the presence of a front vs. back stem-initial vowel. In our *szél* vs. *cél* pairs of stimuli, if systematic sub-categorical differences are found in the transparent vowels, then the source of these differences cannot be ascribed to another vowel within the same stem. The results were, first, that 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. [i:] in *ír*, taking back suffixes, compared to [i:] of *hír*, taking front suffixes, is less advanced when these stems are produced in bare form (no suffixes). Because these monosyllabic stimuli were presented in isolation, the observed sub-phonemic differences cannot be attributed to contextual coarticulation. These differences must be part of the speakers' knowledge of these stems.

To review, then, the main result of the above experiments is 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. The non-linearity in the articulatory-acoustic relations in these vowels, discussed in the context of Stevens' proposals, provides a way to understand why the articulatory differences revealed in these experiments cause minimal differences in the acoustic output of these vowels. It seems reasonable to say that in impressionistic transcriptions these vowels are denoted with a phonemically invariant category even though there are systematic articulatory differences. For other research providing additional evidence for the acoustic stability of [i] and [e], manifested as resistance to coarticulation from adjacent vowels, see Recasens (1999) and Beddor *et al.* (2001).

The hypothesis that transparency has a basis in non-linearities between articulation and acoustics can be extended to at least two other cases of transparency in harmony. In ATR harmony, we discussed articulatory and perceptual factors contributing to limited contrast potential in the class of vowels commonly exhibiting transparency in these harmony systems. As noted, in Kinande 'tongue root' harmony, articulatory and acoustic data also indicate that the low vowel /a/ is an integral part of the harmony domain (Gick *et al.* 2006, Kenstowicz 2009). In the case of Mongolian, where [i, ɪ] are transparent to the spreading of rounding, we see no principled reason why the same hypothesis would not be applicable. If the phonetics of 'rounding' is pursued with some care (Goldstein 1991, Disner 1983), lip posture can be hypothesized to spread through the intervening [i] without a substantial effect on its acoustics. Overall, then, the plausible hypothesis is that transparency is not failure to participate in harmony but failure to produce salient acoustic consequences of harmony on a specific class on segments. Kaun (1995) expresses a similar intuition, that for transparent vowels their "occurrence does not constitute a substantial interruption of the signal associated with the extended feature" (p. 142).

The hypothesis grounding transparency in articulatory-acoustic relations may also allow us to understand why certain vowels exhibit transparency but other similar vowels exhibit opacity. To illustrate this, consider that one important generalization in the phonological patterning of transparency in 'palatal' harmony systems concerns front round vowels. Phonologically, front round vowels do not behave transparently. 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*, **parfüm-nak* 'perfume-DATIVE', *tök-nek*, **tök-nak* 'pumpkin-DATIVE'). In contrast, front unround vowels can be followed by front or back suffixes. Whence the difference in harmonic patterning between [y] and [i]? The two vowels are very similar in terms of their lingual articulation. This is illustrated in (27) showing ultrasound traces of tongue shapes for the Hungarian vowels /e/ [ɛ], /í/ [iː], /é/ [eː], and /ü/ [y], extracted from identical consonantal context /bVb/ (Benus, Gafos & Goldstein 2004).

(27) Lingual shapes of [ɛ] (black), [i] (blue), [eː] (green), [y] (red), with two traces per vowel



The only remaining source of difference between [y] and [i] is their rounding. 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 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. Figure 3 below 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 Figure 3 are based on previously reported data. Specifically, the elongation of the vocal tract for [y] as compared to [i] (white boxes) by rounding and the lowering of the larynx as a compensation for rounding have been documented in Wood (1986). The similarity in the horizontal position of the palatal constrictions (the black boxes) has also been previously described (e.g. Wood 1986: 393) and was confirmed in Benus' (2005) Hungarian data. The relative fronting of the region with insensitivity to articulatory perturbation (grey box) was demonstrated in nomograms of formant resonances in Stevens (1989: 17) and Wood (1986: 396).

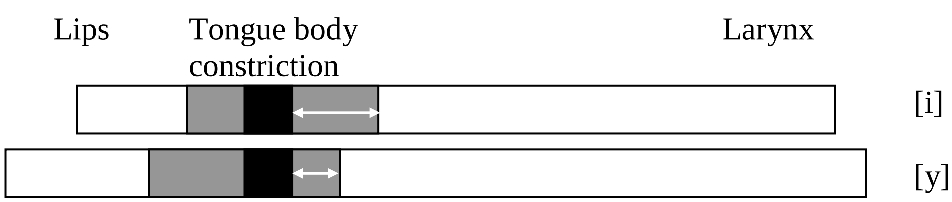


Figure 3. Illustration of the quantal differences between [i] and [y].

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. 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* 'paper-DATIVE' vs. *parfüm-nek* '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.

To summarize, the evidence reviewed indicates that a plausible phonetic basis for transparency and opacity can be formulated by reference to the link between articulation and acoustics.

5. Prospects

We have reviewed theoretical and experimental work on transparent and opaque vowels in vowel harmony. Here, we highlight some directions of future work.

Just as in other areas of phonological patterning, our understanding of transparency and opacity has been increasingly informed by the availability of new experimental methods. Yet, much remains to be done on the experimental side. The main aim should be gaining a more rigorous empirical foundation. Phonological theorizing has relied heavily on impressionistic descriptions of data. As we have seen, in the few cases of harmony which have been examined with experimental methods (Benus 2005, Gick *et al*. 2006, Kenstowicz 2009), the data tell us something new.

On the side of theory, in turn, insights from theoretical analyses should be integrated with the new data patterns. Another way to express this is to say that high-level phonological theory should make predictions about results that could be obtained in future experiments. It is this integration between theory and rigorous data that seems to us most likely to lead to a deeper understanding of the phenomena at hand.

Closely related to the aim of gaining a better grip on the data is research on perception. The experimental findings from Hungarian and Kinande reviewed above show that transparent vowels have two variants depending on the harmonic type in which they appear. For example, the Hungarian vowels {[i:], [i], [e:]} show 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. Ultimately, then, connected to this line of research must be perception experiments, testing the ability of Hungarian listeners to differentiate variably retracted transparent vowels. In turn, this would establish links between this domain of work and research on the fundamental phonological topic of neutralization. The observed differences in the production of Hungarian transparent vowels in the two harmonic types 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 (Dinnsen 1985, Port & O'Dell 1985, Slowiaczek & Dinsen 1985, Fougeron & Steriade 1993, Charles-Luce 1993, 1997, Piroth & Janker 2004, Warner *et al.* 2004; see also the discussion in Port 1996 and 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 (Port & Crawford 1989, Ernestus & Baayen 2006). Similar studies should be done for vowel harmony and specifically for transparent vowels in opposing harmonic contexts.

Furthermore, evidence from other harmony processes would provide a broader perspective on the central issues, expanding and strengthening the basis on which a general understanding of transparency and opacity will rest. Currently, the few cases that have been examined experimentally provide evidence converging with the main results reviewed in this chapter. The first is a study by Cohn (1990) on a case of nasal harmony in Sundanese. Within a Sundanese word, nasality spreads rightward from a nasal consonant until it encounters a supralaryngeal consonant, e.g. [ɲa r] 'say', but [ŋatur] 'arrange'. There is a context where the process seems to affect non-contiguous sequences of vowels, a potential case of a long distance assimilation: the laryngeals /h ʔ/ can intervene in the domain of nasal spread as if they were skipped by the spreading, e.g. [ ] 'take sides' and [ ] 'dry'. Using oral/nasal airflow traces, however, Cohn presents evidence that these 'transparent' consonants are in fact nasalized. A parallel finding on transparency is reported in a study of consonant harmony in Kinyarwanda (Walker et al. 2008). The language shows a harmony process described as affecting coronal fricatives, /ku-sooz-a/ → [gusooza] 'to finish', /ku-sooz-iiʂ-a/ → [guʂooʐiiʂa] 'to cause to finish'. In […ʂVmVʐ…] and […ʂVkVʐ…] contexts, where the two fricatives are not in adjacent syllables, consonant harmony applies optionally. When it does apply, the first fricative takes on the retroflex property of the second. Non-coronal consonants such as [k] and [m] are described as being transparent to the harmony process. The kinematic results of Walker et al. (2008) indicates that the tip-blade posture during [m] and [k] in the harmony context was not significantly different from that of the retroflex fricatives. Here too then transparent segments, which at first appeared to be skipped on the basis of impressionistic descriptions, participate articulatorily in the harmony process.

References

Akinlabi, Akinbiyi (1994). Featural alignment. Ms., Rutgers University.

Alderete, John. 1997. 'Dissimilation as Local Conjunction', in Kiyomi Kusumoto (ed.), *Proceedings of NELS 27*, GLSA, University of Massachusetts, Amherst, pp. 17-31.

Anderson, L. (1980). Using asymmetrical and gradient data in the study of vowel harmony. In R. Vago (ed.) *Issues in Vowel Harmony* (pp. 271-340). Amsterdam: John Benjamins.

Anderson, S. R. (1980). Problems and perspectives in the description of vowel harmony. In R. Vago (ed.), *Issues in vowel harmony* (pp. 1- 48). Amsterdam: John Benjamins.

Anderson, S. R. (1981). Why phonology isn't natural? *Linguistic Inquiry* 12:4, 493-539.

Archangeli, Diana and Douglas Pulleyblank. (1994). *Grounded phonology*. MIT Press, Cambridge.

Archangeli, Diana and Douglas Pulleyblank. (2007). "Harmony," in Paul de Lacy, ed., *The Cambridge Handbook of Phonology*, 353-378. Cambridge: Cambridge University Press.

Baković, Eric. (2000). *Harmony, dominance and control.* PhD dissertation, Rutgers.

Baković, Eric and Colin Wilson. (2000). Transparency, strict locality, and targeted constraints, In *Proceedings of WCCFL 19*, Cascadilla Press, Somerville.

Beckman, Jill. (1998). *Positional faithfulness*. Ph.D dissertation, University of Massachusetts, Amherst.

Beckman, M.E., Jung, T.-P., Lee, S., de Jong, K., Krishnamurthy, A. K., Ahalt, C. S., Cohen, K. B., & Collins, M. J. (1995). Variability in the production of quantal vowels revisited. *Journal of the Acoustical Society of America, 97,* 471-490.

Beddor, P. S., Krakow, R. A., & Lindemann, S. (2001). Patterns of perceptual compensation and their phonological consequences. In E. Hume & K. Johnson (eds.), *The role of perceptual phenomena in phonology* (pp. 55-78). San Diego: Academic Press.

Beddor, P. S., Harnsberger, J., & Lindemann, S. (2002). Language-specific patterns of vowel-to-vowel coarticulation: acoustic structures and their perceptual correlates. *Journal of Phonetics, 30,* 591-627.

Benuš, Štefan. (2005). *Dynamics and transparency in vowel harmony*. Unpublished Ph.D. Dissertation, New York University.

Benuš, Š., Gafos, A., & Goldstein, L. (2004). *Phonetics and phonology of transparent vowels in Hungarian*. In P.M. Nowak, C. Yoquelet & D. Mortensen (Eds.), *Proceedings of the 29th Annual meeting of the Berkeley Linguistic Society* (pp. 485-497). Berkeley Linguistic Society.

Benuš, Š., & Gafos, A. (2005). Qualitative and quantitative aspects of vowel harmony: A dynamics model. In B. G. Bara, L. Barsalou & M. Bucciarelli (eds.), *CogSci2005, XXVII Annual Conference of the Cognitive Science Society (Stresa, Italy, 2005)* (pp. 226-231). New Jersey: Lawrence Erlbaum.

Benuš, Š., & Gafos, A. (2007). *Articulatory* characteristics of Hungarian 'transparent' vowels. *Journal of Phonetics* 35 (3), 271-444

Boyce, S. E. 1988. The Influence of Phonological Structure on Articulatory Organization in Turkish and in English: Vowel Harmony and Coarticulation. PhD dissertation, Yale University, New Haven, Conn.

Boyce, S. E. 1990. Coarticulatory Organization for Lip Rounding in Turkish and English. Journal of the Acoustical Society of America 88, 2584-2595.
Burzio, L. (1994). *Principles of English stress*. Cambridge: Cambridge University Press.
Campbell, L. (1980). The psychological and sociological reality of Finnish vowel harmony. In R. Vago (ed.), *Issues in vowel harmony*, (pp. 245-271). Amsterdam: John Benjamins.
Charles-Luce, J. (1993). The effects of semantic context on voicing neutralization. *Phonetica*, 50, 28-43.
Charles-Luce, J. (1997). Cognitive factors involved in preserving a phonemic contrast. *Language and Speech, 40,* 229-248.
Chomsky, N., & Halle, M. (1968). *The sound pattern of English.* New York: Harper and Row. (Reprinted: MIT Press, 1991.)
Clements, G. N. 1977. Neutral Vowels in Hungarian Vowel Harmony: an Autosegmental Interpretation. In Proceedings of the North Eastern Linguistic Society 7, 49-64.
Clements, G. N. (1980) Vowel harmony in nonlinear generative phonology. Bloomington: Indiana University Linguistics Club.
Clements, G. N. (1985) Akan vowel harmony: A nonlinear analysis. In D. Goyvaerts, (ed.), *African Linguistics: Essays in memory of M. W. K. Semikenke,* (pp. 55-98), Amsterdam: Benjamins.
Clements, G. N. (1990). The hierarchical representation of vowel height. Ms., Cornell University.
Clements, G. N. (1991). Vowel height assimilation in Bantu languages. *Working Papers of the Cornell Phonetics Laboratory* 5: 37-76.
Cohn, A. 1990. *Phonetic and Phonological Rules of Nasalization*. UCLA PhD dissertation. Distributed as *UCLA Working Papers in Phonetics*, 76.
Cole, Jennifer S. & Charles Kisseberth (1994) An optimal domains theory of harmony. *Studies in the Linguistic Sciences* 24: 1-13.
Cole, Jennifer S. & Charles Kisseberth (1995). Paradoxical strength conditions in harmony systems. *NELS* 25. 17-29.
D'Imperio, M. & Rosenthall, S. (1999). Phonetics and Phonology of Main Stress in Italian. *Phonology* 16: 1-28.
Dinnsen, D. A. (1985). A re-examination of phonological neutralization. *Journal of Linguistics, 21,* 265-279.
Disner, Sandra F. (1983). *Vowel quality: The relation between universal and language- specific factors*. Ph.D. dissertation, University of California, Los Angeles.
Dolphyne, F. A. (1988). *The Akan (Twi-Fante) Language: Its Sound Systems and Tonal Structure*. Accra, Ghana: Ghana Universities Press.
Ernestus, M., & Baayen, H. (2006). The functionality of incomplete neutralization in Dutch: The case of past tense formation. In L. Goldstein, D. Whalen & C. Best (eds.), *Varieties of phonological competence (Laboratory phonology 8)* (pp. 27- 49). Berlin, New York: Mouton de Gruyter.
Engstrand, O. 1981. Acoustic Constraints of Invariant Input Representation? An Experimental Study of Selected Articulatory Movements and Targets. Reports of the Uppsala University Department of Linguistics 7, 67-94. Department of Linguistics, Uppsala, Sweden.
Farkas, D., & Beddor, P. S. (1987). Privative and equipollent backness in Hungarian. In A. Bosch, B. Need & E. Schiller (eds.), *23rd Annual Regional Meeting of the Chicago Linguistics Society. Part Two: Parasession on Autosegmental and Metrical Phonology*, 90-105. Chicago, IL: Chicago Linguistics Society.
Farnetani, E., Vagges, K., & Magno-Caldognetto, E. (1985). Coarticulation in Italian VtV sequences: A palatographic study. *Phonetica*, *42*, 78-99.
Fanti, R. (1938). Note Fonetiche e Morfologiche Sul Dialetto di Ascrea (Rieti). *L'Italia Dialettale*. 14: 201-218.
Fanti, R. (1939). Note Fonetiche e Morfologiche Sul Dialetto di Ascrea (Rieti). *L'Italia Dialettale*. 15: 101-135.
Fanti, R. (1940). Note Fonetiche e Morfologiche Sul Dialetto di Ascrea (Rieti). *L'Italia Dialettale*. 16: 77-140.
Fónagy, I. (1966). Iga es ige. *Magyar Nyelv, 62,* 323-324.
Fowler, C. A. (1983). Converging sources of evidence on spoken and perceived rhythms of speech: cyclic production of vowels in monosyllabic stress feet. *Journal of Experimental Psychology: General, 112,* 386-412.
Fougeron, C., & Steriade, D. (1997). Does deletion of French schwa lead to neutralization of lexical distinctions? In *Euro-Speech 1997: Proceedings of the 5th European conference on speech communication and technology* (University of Patras, Greece), Vol. 7: 943-946.
Gafos, A. (1999). *The articulatory basis of locality in phonology*. New York: Garland.
Gafos, Adamantios I. and Linda Lombardi. 1999. 'Consonant Transparency and Vowel Echo', in P. Tamanji, M. Hirotani, and N. Hall (eds.), *Proceedings of NELS 29*, GLSA, University of Massachusetts, Amherst, pp. 81-96.
Gafos, A. and Benuš, Š. 2003. *On neutral vowels in Hungarian*. Proceedings of the 15th International Congress of Phonetic Sciences, M.-J. Solé, D. Recasens & J. Romero (eds.), 77-80. Universitat Autònoma de Barcelona.
Gafos, A., & Benuš, Š. (2006). Dynamics of phonological cognition. *Cognitive Science 30*, 905-943.

Gick, B., Pulleyblank, D., Campbell, F., & Mutaka, N. (2006). Low vowels and transparency in Kinande vowel harmony. *Phonology, 23*, 1-20.
Goldsmith, J. 1985. Vowel harmony in Khalka Mongolian, Yaka, Finnish and Hungarian. Phonology Yearbook 2, 253-275.
Goldsmith, J. (1993). Harmonic phonology. In J. Goldsmith (Ed.), *The last phonological rule* (pp. 21-60). Chicago: University of Chicago Press.
Goldstein, Louis. 1991. Lip rounding as side contact. Proceedings of the 12th International. Congress of Phonetic Sciences, Aix-en-Provence, Vol 1: 97-101.
Gordon, Matthew. (1999). The "neutral" vowels of Finnish: How neutral are they? *Linguistica Uralica, 1*, 17-21.
Gordon, Matthew. (2006). Phonetics of harmony systems. In: Keith Brown, (Editor-in-Chief) *Encyclopedia of Language & Linguistics, Second Edition*, volume 9, pp. 418-425. Oxford: Elsevier.
Halle, M., Stevens, K., 1969. On the feature ''Advanced Tongue Root." Quarterly Progress Report 94, Research Laboratory of Electronics, MIT, Cambridge, MA, pp. 209–215.
Harrison, D., Dras, M., & Kapicioglu, B. (2002). Agent-based modeling of the evolution of vowel harmony. In M.
Hirotani (ed.), *Proceedings of NELS 32* (pp. 217–236).
Hayes, B. & Londe, Z. (2006). Stochastic phonological knowledge: The case of Hungarian vowel harmony. *Phonology, 23,* 59-104.
Hulst, H.G. van der. (1985). Vowel harmony in Hungarian. A comparison of segmental and autosegmental analyses. In H. van der Hulst & N. Smith (eds.), *Advances in nonlinear phonology*, 267-303. Dordrecht: Foris.
Hulst, H.G. van der, & Weijer, J. van de. (1995). Vowel harmony. In J. Goldsmith (ed.), *The handbook of phonological theory* (pp. 495-534). Oxford: Blackwell.
Itô, Junko and Armin R. Mester. 1995. Japanese phonology. In John A. Goldsmith (ed.) *The Handbook of Phonological Theory*, Cambridge, MA & Oxford: Blackwell. 817-838.
Itô, Junko and Armin R. Mester. 1997. 'Markedness and Word Structure: OCP Effects in Japanese', unpublished manuscript., University of California at Santa Cruz, California. [Available on the Rutgers Optimality Archive as ROA #255.]
Johnson, K. (1996). Speech perception without speaker normalization. In K. Johnson and J.W. Mullennix (eds.), *Talker Variability in Speech Processing* (pp. 145-166). San Diego: Academic Press.
Jun, Jongho. (1995). Perceptual and articulatory factors in place assimilation: An Optimality Theoretic Approach. Ph.D. dissertation, UCLA.
Jungraithmayr, H. (1971). The Tangale vowel system reconsidered. *Journal of African Languages* 10: 28-33.
Kager, Renee. (1999). *Optimality theory*. Cambridge: Cambridge University Press.
Kaun, A. (1995). *The typology of rounding harmony: An optimality theoretic approach.* Ph.D. Dissertation, UCLA. [Published as UCLA Dissertations in Linguistics, No. 8].
Kertész, Zsuzsa. 2003. Vowel harmony and the stratified lexicon of Hungarian. *The Odd Yearbook* 7, 62-77.
Kenstowicz, Michael. 1994. *Phonology in Generative grammar*. Cambridge, MA: Blackwell.
Kenstowicz, Michael. 2009. Two notes on Kinande vowel harmony. *Language Sciences* 31, 248-270.
Kenstowicz, Michael and Kisseberth, Charles. (1979). *Generative phonology*. San Diego: Academic.
Kidda, M. (1985). *Tangale phonology: a descriptive analysis*. Ph.D. dissertation, University of Illinois.
Kiparsky, Paul. 1981. Vowel Harmony. Ms. Stanford University, Stanford, Calif.
Kiparsky, Paul and Karl Pajusalu. 2003. Towards a Typology of Disharmony. *The Linguistic Review* 20:217-241.
Kirchner, R. (1993) Turkish vowel harmony and disharmony: An Optimality Theoretic Account. Paper presented at Rutgers Optimality Workshop I, October 22, 1993.
Kirchner, R. (1999). Preliminary thoughts on 'phonologization' within an exemplar-based speech processing system. In M. Gordon (ed.), *UCLA Working Papers in Linguistics 1* (pp. 207-231).
Kramer, Martin. (2003). *Vowel harmony and correspondence theory*. Berlin: Mouton de Gruyter.
Ladefoged, P. (1964). *A Phonetic Study of West African Languages*. Cambridge University Press. Reprinted 1968.
Labov, W., Karen, M., & Miller, C. (1993). Near mergers and the suspension of phonemic contrast. *Language Variation and Change, 3,* 33-74.
Lindau, Mona. (1978). Vowel features. *Language* 54, 541–563.
Magen, H. (1984). Vowel-to-vowel coarticulation in English and Japanese. *Journal of the Acoustical Society of America, Supplement 1*, 75: S41.
Magen, H. (1997). The extent of vowel-to-vowel coarticulation in English. *Journal of Phonetics* 25: 187-205.
McAllister, R. 1978. Temporal asymmetry in labial coarticulation. *Working Papers, Institute of Linguistics, Stockholm University* 35, 1-29.
McCarthy, John J. (1989). Linear order in phonological representation. *Linguistic Inquiry* 20, 71-99.
McCarthy, John J. (2003). On targeted constraints and cluster simplification. *Phonology* 19, 273-292.

McCarthy, John J. and A. Prince. (1993). *Generalized Alignment*. Ms., University of Massachusetts, Amherst, and Rutgers University, New Brunswick, NJ.

Mutaka, Ngessimo M. (1994). *The lexical tonology of Kinande*. Munich: Lincom Europa.

Ní Chiosáin, Máire & Padgett, Jaye. (2001). Markedness, segement realization, and locality in spreading. In Lombardi, Linda (ed.) *Segmental phonology in Optimality Theory: Constraints and representations*. Cambridge: Cambridge University Press. 118-156.

Ohala, J. (1994a). Towards a universal, phonetically-based, theory of vowel harmony. *Proceedings of International Conference on Spoken Language Processing* (pp. 491-494).

Ohala, J. (1994b). Hierarchies of environments for sound variation; plus implications for "neutral" vowels in vowel harmony. *Acta Linguistica Hafniensia, 27,* 371-382.

Öhman, Sven. (1966). Coarticulation in VCV utterances: Spectrographic measurements. *Journal of the Acoustical Society of America, 39,* 151-168.

O'Keefe, M. (2003) Akan Vowel Harmony. Unpublished ms., Swarthmore College.

Perkell, J. S. 1986. Coarticulation Strategies: Preliminary Implications of a Detailed Analysis of Lower Lip Protrusion Movements. Speech Communication 5, 47-68.

Pierrehumbert, J. (2001). Exemplar dynamics: word frequency, lenition, and contrast. In J. Bybee and P.J. Hooper (eds.), *Frequency and the emergence of linguistic structure* (pp. 137-158). Amsterdam: John Benjamins.

Piroth, H. G. & Janker, P. M. (2004). Speaker-dependent differences in voicing and devoicing of German obstruents. *Journal of Phonetics, 32,* 81–109.

Port, R. F. & O'Dell, M. (1985). Neutralization of syllable-final voicing in German. *Journal of Phonetics, 13,* 455-471.

Port, R., & Crawford, P. (1989). Incomplete neutralization and pragmatics in German. *Journal of Phonetics, 17,* 257–282.

Prince, A., & Smolensky, P. (1993/2004). *Optimality theory: Constraint interaction in generative grammar.* Technical Report CU-CS-696-93, Department of Computer Science, University of Colorado at Boulder, and Technical Report TR-2, Rutgers Center for Cognitive Science, Rutgers University, New Brunswick, NJ, April 1993. [Published: Blackwell, 2004].

Prince, A., & Smolensky, P. (1997) Optimality: from neural networks to universal grammar. *Science*, 275, 1604-1610.

Pulleyblank, D. (1996). Neutral Vowels in Optimality Theory: A Comparison of Yoruba and Wolof. *Canadian Journal of Linguistics*, 41:4, 295-347.

Przezdziecki, M. (2005). *Vowel Harmony and Coarticulation in Three Dialects of Yoruba: Phonetics Determining Phonology*. Ph.D. dissertation, Cornell University.

Recasens, D. (1987). An acoustic analysis of V-to-C and V-to-V coarticulatory effects in Catalan and Spanish VCV sequences. *Journal of Phonetics, 15,* 299-312.

Recasens, D. (1999). Lingual coarticulation. In W.J. Hardcastle & N. Hewlett (eds.), *Coarticulation: Theory, data and techniques* (pp. 78-104). Cambridge, UK: Cambridge University Press.

Rialland, Annie & Redouanne, Djamouri. (1984). Harmonie vocalique, consonantiue et structures de dépendance dans le mot en mongol khalkha. *Bulletin de la Société de Linguistique de Paris* 79.1: 333-383.

Ringen, Catherine. (1975). *Vowel harmony: theoretical implications*. Ph.D. dissertation, Indiana University. Published 1988, New York: Garland.

Ringen, Catherine. (1988). Transparency in Hungarian vowel harmony. *Phonology* 5: 327-342.

Ringen, C., & Kontra, M. (1989). Hungarian neutral vowels. *Lingua, 78,* 181-191.

Ringen, Catherine and Vago, Robert. (1998). Hungarian vowel harmony in Optimality Theory. *Phonology* 15: 393-416.

Schachter, Paul and Fromkin, Victoria. (1968). *A Phonology of Akan: Akuapem, Asante and Fante*. Working Papers in Phonetics No. 9, UCLA.

Schlindwein, Deborah. (1987). P-bearing units: a study of Kinande vowel harmony. *NELS* 17: 551-567.

Siptár, P. & Törkenzy, M. (2000). *The phonology of Hungarian*. Oxford: Oxford University Press.

Slowiaczek, L. & Dinnsen, D. (1985). On the neutralizing status of Polish word-final devoicing. *Journal of Phonetics, 13,* 325-341.

Smolensky, Paul. 1993. Harmony, markedness, and phonological activity. Ms., University of Colorado, Boulder. (available as ROA-87 from the Rutgers Optimality Archive).

Smolensky, Paul. 1995. 'On the Internal Structure of the Constraint Component *Con* of UG', handout of talk presented at UCLA, April 7, 1995.

Smolensky, Paul. 1997. 'Constraint Interaction in Generative Grammar II: Local Conjunction (or, Random Rules in Universal Grammar)', paper presented at the Hopkins Optimality Theory Workshop, University of Maryland Mayfest. Baltimore.

Steriade, D. (1987). Redundant values. Papers from the Twenty-Third Annual Regional Meeting of the Chicago Linguistic Society, Part II (CLS 23), ed. Bosch, A., B. Need, and E. Schiller, 339-362. Chicago Linguistic Society, Chicago, Ill.

Steriade, D. (1995). Underspecification and markedness. In J. Goldsmith, (ed.) *The Handbook of Phonological Theory*, 114-174. Cambridge, Mass.: Blackwell Press.

Steriade, D. (1997). Phonetics in phonology: The case of laryngeal neutralization. Ms., UCLA.

Steriade, D. (2000). The phonology of perceptibility effects: The P-map and its consequences for constraint organization. Ms., UCLA.

Stevens, K. N. (1972). The quantal nature of speech : evidence from articulatory-acoustic data. In D. Denes (ed.), *Human communication: A unified view* (pp. 51-66). New-York: McGraw-Hill.

Stevens, K. N. (1989). On the quantal nature of speech. *Journal of Phonetics, 17,* 3-45.

Stevens, K.N., Keyser, S. K., & Kawasaki, H. (1986). Toward a Phonetic and Phonological Theory of Redundant Features. In J. Perkell and D. Klatt (eds.), *Invariance and Variability in Speech Processes*. London: Lawrence Erlbaum Associates.

Suomi, K. (1983). Palatal harmony: A perceptually motivated phenomenon? *Nordic Journal of Linguistics* 6: 1-35.

Svantesson, Jan-Olof, Tsendina, Anna, Karlsson, Anastasia, and Franzén, Vivian. (2005). *The phonology of Mongolian*. New York: Oxford University Press.

Tiede, Mark K. (1996). An MRI-based study of pharyngeal volume contrasts in Akan and English. *JPh* 24, 399–421.

Vago, Robert. (1976). Theoretical implications of Hungarian vowel harmony. *Linguistic Inquiry* 7: 243-263.

Vago, R. M. (1980). *The sound pattern of Hungarian*. Washington: Georgetown University Press.

van der Hulst, Harry & van de Weijer, Jeroen. (1995). Vowel harmony. In J. Goldsmith, (ed). *The Handbook of Phonological Theory*. 495-534.

Välimaa-Blum, R. (1999). A feature geometric description of Finnish vowel harmony covering both loans and native words. *Lingua* 108, 247-268.

Walker, R. (2005). Weak triggers in vowel harmony. *Natural Language and Linguistic Theory* 23, 917-989.

Walker, R. (2010) Nonmyopic harmony and the nature of derivations. *Linguistic Inquiry* 41.1, 169-179.

Walker, R., Byrd, D., Mpiranya, F. 2008. An articulatory view of Kinyarwanda coronal harmony. *Phonology* 25, pp. 499-535.

Warner, N., Jongman, A., Sereno, J., & Kemps, R. (2004). Incomplete neutralization and other sub-phonemic durational differences in production and perception: evidence from Dutch. *Journal of Phonetics* 32, 251–276.

Wells, J. C. (1962). A Study of the Formants of the Pure Vowels of British English. Unpublished Ph.D. dissertation, University of London.

Wiik, K. (1995). Finno-Ugric prosodic substrata in Germanic languages and vice versa. *Proceedings of the XIIIth International Congress of Phonetic Sciences*, Vol.4, 168-171.

Wilson, Colin. (2000). Targeted constraints: An approach to contextual neutralization in Optimality Theory. Ph.D dissertation, Johns Hopkins University.

Wilson, Colin. (2001). Consonant cluster neutralization and targeted constraints. *Phonology* 18, 147-197.

Wood, S. (1979). A radiographic analysis of constriction location for vowels. *Journal of Phonetics* 7, 25-43.

Wood, S. (1986). The acoustic significance of tongue, lip, and larynx maneuvers in rounded palatal vowels. *Journal of the Acoustical Society of America* 80, 391-401.