Neuromagnetic reflections of harmony and constraint violations in Turkish

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Abstract

Vowel harmony is a phonotactic principle that requires adjacent vowels to agree in certain vowel features. Phonological theory considers this principle to be represented in one's native grammar, but its abstractness and perceptual consequences remain a matter of debate. In this paper, we are interested in the brain's response to violations of harmony in Turkish. For this purpose, we test two acoustically close and two acoustically distant vowel pairs in Turkish, involving different kinds of harmony violations. Our measure is the Mismatch Negativity (MMN), an automatic change detection response of the brain that has previously been applied for the study of native phoneme representations in a variety of languages. The results of our experiment support the view that vowel harmony is a phonological principle with a language-specific long-term memory representation. Asymmetries in MMN responses support a phonological analysis of the pattern of results, but do not provide evidence for a pure acoustic or a pure probabilistic approach. Phonological analyses are given within Optimality Theory (OT) and within an underspecification account.

1. Introduction

Knowledge about a language necessarily pertains to the representation of distinctive speech sounds (phonemes). In addition, native speakers implicitly know which phonemes may co-occur within a word or follow each other in their language. In phonological theory, these abstract principles of restricting possible sequences of speech sounds are referred to as phonotactic constraints. They belong to the phonological grammar of a language and are represented independently of the set of possible speech sound representations (Kenstowicz 1994); that is, languages with the same speech sound inventories can have different phonotactic patterns.

Behavioral (e.g., Dupoux et al. 2001) and electrophysiological research (e.g., Dehaene-Lambertz, Dupoux, and Gout 2000) has shown that phonotactic knowledge

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deeply affects speech perception at the earliest moments in speech processing. Dupoux et al. (2001) presented Japanese listeners with illegal consonant clusters in pseudo-words, contrasting in lexical neighborhood density. Lexical neighborhood did not affect the perception of an illusory vowel that compensated for the phonotactic violations in Japanese. The same effect was studied by Dehaene-Lambertz, Dupoux, and Gout (2000) using event-related potentials (ERPs) to assess the consequences of phonotactic violations for speech perception. These experiments suggest that phonotactic constraints exert influences on the recognition of speech at very early, pre-lexical stages. Further, event-related potential (ERP) studies have suggested that phonotactic information is represented in a language-specific way (Aaltonen et al. 2008), similar to the representation of phonemes (Näätänen et al. 1997).

Within phonological theory, phonotactics has been analyzed using rules (e.g., Sommerstein 1974), constraints and repairs (e.g., Paradis 1987; Calabrese 1995), or constraint interactions as proposed by Optimality Theory (OT; Prince and Smolensky 2004). A phonotactic phenomenon that has been given considerable attention in recent years is vowel harmony, i.e., the agreement of particular vowel features within words. Approaches within OT (Kirchner 1993; Kaun 1994; Beckman 1997; Benua 1997; Krämer 1999, 2003; Bakovic 2000, 2003; Finley 2008; Sasa 2009) and in other procedural or auto-segmental frameworks (Lees 1961; Clements 1977; Clements 1980; Halle and Vergnaud 1980; Clements and Sezer 1982; Sezer 1986; Halle, Vaux, and Wolfe 2000; Kabak 2007; Mailhot and Reiss 2007; Samuels 2009) all try to account for restrictions on harmony that potentially lead to disharmonic sequences.

A fruitful endeavor for the interdisciplinary study of language competence and comprehension is to relate phonological theory to studies of cortical processing. To what degree can constraint or rule-based approaches predict and account for brain electric or magnetic responses to violations of vowel harmony? In this article we will apply these approaches to Turkish vowel harmony from two different angles. First, we briefly summarize two ways of accounting for the phenomenon within phonological theory. Second, we try to assess the extent of neurophysiological consequences of harmony violations on the basis of vowel sequences without a given word context. Even though harmony operates in a limited domain in Turkish (e.g., the word), it might be that at some level of processing, harmony as a phonotactic principle is independent of lexical representations, and therefore, independent of the word domain. We therefore think it is fruitful to look at single vowel sequences with a neurophysiological measure providing us with very good temporal resolution, as illustrated in the experimental section in more detail. Finally, Turkish is one of the few languages in which featural conflicts responsible for harmony violations do not parallel gradient acoustic distances between vowel phonemes (this point is discussed further below). Thus, our experimental paradigm is ideally suited to assess vowel harmony from an abstract phonological perspective.

Table 1. *Phonological feature specifications of Turkish vowel system.*

	Front		Back	
	Unrounded	Rounded	Unrounded	Rounded
High	i	y	ɯ	u
Low	ɛ	ɔ	ɑ	œ

Table 2. *Turkish vowel harmony, examples based on Clements and Sezer (1982). Vowel correspondences: ü = [y], e = [ɛ], a = [a], o = [ɔ], ɨ = [ɯ], ö = [œ].*

Noun	Gen Sing. /$V_{[+high]}$/n	Nom Plural l/$V_{[-high]}$/r	Gloss
yüz	yüzün	yüzler	*'face'*
pul	pulun	pullar	*'stamp'*
ip	ipin	ipler	*'rope'*
el	elin	eller	*'hand'*
sap	sapɨn	saplar	*'stalk'*
kɨz	kɨzɨn	kɨzlar	*'girl'*
köy	köyün	köyler (*köylör)	*'village'*
son	sonun	sonlar (*sonlor)	*'end'*

2. Vowel harmony in Turkish

Turkish has a symmetrical eight-vowel system, distinguishing between high/non-high, rounded/unrounded, and front/back vowels (Lees 1961, cf. Table 1).

Within a word, vowel sequences are generally harmonic with respect to place (front/back) and roundedness (rounded/unrounded). For instance, the genitive singular suffix consists of a high vowel that agrees in roundedness and place with the stem vowel (*yüz-ü̲n 'face':* front rounded [y]; *sap-ɨ̲n 'stalk':* back unrounded [ɯ], Table 2). Place and roundedness features symmetrically spread from stem vowels to suffix vowels (in the above examples from [y] in *yüz* to the high suffix vowel, yielding [y], and from [a] in *sap* to the suffix vowel, yielding [ɯ], cf. Clements and Sezer 1982; Halle 1995). Apart from exceptionally opaque vowels resisting harmony, there are vowel sequences in Turkish that systematically do not fully harmonize. This is accounted for by a constraint that non-initial vowels and vowels in suffixes can only become round if they are high (cf. Sezer 1986, see Table 2; there are other ways to express this condition, see for example Cole and Trigo 1988).

Auto-segmental approaches to Turkish vowel harmony (Clements 1977; Clements 1980; Halle and Vergnaud 1980; Clements and Sezer 1982) assume that harmonizing vowels (i.e., harmony undergoers) are unspecified for the respective harmonizing feature. This is illustrated in Table 2. The genitive suffix vowel is thus only specified for height (i.e., [+high]) and receives roundedness and place

Table 3. *Turkish lexical feature specifications according to Kabak (2007).*

		i	y	ɯ	u	ɛ	œ	ɑ	ɔ
rounding	LAB		✓		✓		✓		✓
place	COR								
	DOR			✓	✓			✓	✓
height	HIGH								
	LOW					✓	✓	✓	✓

features from the harmony trigger (here: the stem vowel). Similarly, the nominative singular suffix vowel is specified for [−high] and again agrees in roundedness and place with the stem vowel.

In this spirit, using a rule-based approach, Kabak (2007) proposes an underspecification approach to Turkish vowels and accounts for vowel harmony in the following way. His first assumption is that front (coronal = [cor]) vowels are underspecified for place of articulation and receive this feature by default feature insertion if the feature dorsal (= [dor]) is not present (cf. Lahiri and Reetz 2002). Second, high vowels are also underspecified and have no underlying tongue height feature. This claim is based on equating the most unmarked vowel with the epenthetic vowel, which is [i] in Turkish. Thus, [low], [dor], and [lab] (= rounded) are the active feature specifications for Turkish. Similar to [cor], [high] is inserted by default rules whenever no other phonological process has provided the underlyingly specified feature [low]. Table 3 illustrates the resulting feature specification for the Turkish vowel system, assuming monovalent features, again following Kabak (2007).

Harmonizing high and/or coronal vowels are accounted for by the default insertion of [high] and [cor], respectively. For instance, *ip-in* (‘of the rope’) contains the underlyingly least marked vowels in stem and suffix position. The surface specifications are derived by default tongue height and place insertion. Harmonizing low and/or dorsal vowels, by contrast, are accounted for by the spreading (i.e., copying) of the specified features [low] and [dor]. The stem vowel in the nominative plural form *kɨz-lar* (‘girls’), for example, is specified for [dor] and spreads this feature onto the plural suffix of which the vowel is underlyingly low, resulting in dorsal and low [a]. Finally, labial harmony is restricted in that [lab] can only spread to vowels that are not specified for tongue height underlyingly, i.e., that are non-low, in effect a complexity condition on derived representations. Therefore, the low plural suffix vowel cannot receive labiality from *son* (‘end’), thus precluding **son-lor* for *son-lar.* The restriction on labial spreading is evaluated on derived representations, i.e., a low, round vowel cannot be derived.

On the other hand, most Optimality Theory approaches to vowel harmony in general and to Turkish vowel harmony in particular refrain from the assumption of underspecification. This is mainly because underspecification does not add much explanatory power to most OT analyses or allegedly requires additional mecha-

Table 4. *OT approach to Turkish vowel harmony, using a subset of constraints from Krämer (1999, 2003), for the derivation of* sonlar *(*'end' *[plural]).*

/son-l$V_{[low]}$r/	S-Ident (Place)	*RoLo	S-Ident (Round)
sonlor		*!	
sonler	*!		*
sonlar			*
sonlör	*!	*	

nisms in some languages (Bakovic 2000, 2003; Finley 2010). However, underspecification is not entirely abandoned in OT analyses (e.g., Inkelas 1995, 1996; Walker 2001). The difference between OT analyses with underspecification and Kabak's (2007) underspecification approach is that Kabak (2007) does not invoke constraint rankings, but rather follows the autosegmental tradition with serially ordered phonological rules.

In the OT framework, directionality of harmony and the occurrence of disharmonic sequences are dealt with by interactions of various different faithfulness and markedness constraints, cast in frameworks of Correspondence Theory (e.g., Benua 1997; Krämer 1999; Rose and Walker 2004), Generalized Alignment (McCarthy and Prince 1993) or Span Theory (McCarthy 2004; Smolensky and Legendre 2006), to name but a few (an extensive discussion of some OT approaches is given in Sasa 2009). Since it is beyond the scope of this study to individually evaluate the neurophysiological predictions of each slightly differing OT approach, we take a simplifying perspective and invoke two faithfulness (to account for place and roundedness harmony) and one markedness constraint (to account for harmony exceptions) in order to account for the Turkish data. These constraints correspond to a subset of constraints from Krämer (1999, 2003; cf. Table 4). Analogous constraints or conditions are present in almost all analyses.

As illustrated in Table 4, place and rounding harmony are accounted for by the surface-identity constraints S-Ident (Place) and S-Ident (Round), respectively, which are violated whenever the corresponding feature is not spread onto the suffix vowel. S-Ident (Place) and S-Ident (Round) are surface-identity constraints and require a vowel to have the same place or roundedness specification as the vowel in the adjacent syllable (Krämer 1999). The two constraints are from the family of Ident(F) constraints (McCarthy and Prince 1995). Note that the S-Ident constraints are very similar to the constraint Agree (e.g., Bakovic 2000).

For the plural of *son 'end'*, the low suffix vowel should correspond in place and roundedness with the rounded back vowel [ɔ]. The constraint S-Ident (Round) requires sufffix vowels to agree in rounding with the stem vowels, i.e., penalizes rounding disagreement (e.g., *sonla̲r*), while the higher-ranked S-Ident (Place) requires suffix vowels to agree in place with the stem vowel, i.e., penalizes place disagreement (e.g., *sonler*). Note that the two constraints include directionality in that the stem vowel determines the specification of the suffix vowel to its right, i.e., they require a right-ward spreading of the stem vowel feature onto the suffix vowel.

The S-Ident (Round) constraint, however, can be violated by certain lexical items that show a specific feature structure. In particular, all non-initial vowels must not be both rounded and low, according to the *RoLo constraint, such that spreading of roundedness (though required by S-Ident (Round)) is penalized. Put differently, this markedness constraint penalizes low round vowels resulting from harmony and again includes a directional assumption. It must prohibit the spreading from roundedness onto an underlyingly low suffix vowel (i.e., the vowel to the right of the stem vowel). It has to outrank the S-Ident (Round) constraints in order to exclude the otherwise harmonic **son-lor* candidate.

As mentioned above, we provide a very simplified OT analysis, neglecting some facets of the *RoLo constraint that are dealt with in more detail in the OT literature (cf. Sasa 2009). We also neglect constraints that would penalize candidates with a high suffix vowel or changes in the stem vowel. This simplification is justified on the basis of the abstract phonotactic principle that we want to test experimentally. Crucially, the simplified analysis accounts for disharmonic vowel sequences by virtue of faithfulness violations, and for the acceptance of disharmonic sequences by virtue of the satisfaction of the higher-ranked *RoLo constraint. Thus, we try overall to disregard the input-output aspects of the problem and treat it as a pure phonotactic phenomenon, where predictions for harmonic vowels are made on the basis of a preceding (stem) vowel. In particular, we are interested to what degree the co-occurrence constraints on Turkish vowels imposed by harmony affect early stages of speech perception. The simplifying assumptions are also motivated by the choice of our experimental methods that bear on underlying phonological properties of a particular sound, followed by another sound that differs in certain phonological dimensions. The experimental methods and how they are related to vowel harmony as a phonotactic principle are elucidated in the next sections.

3. Predicting brain responses from illicit vowel sequences

We assume – in accordance with the phonological analyses – that vowel harmony in Turkish is an abstract phonological principle, represented as knowledge of phonological grammar that is independent of lexical entries or phoneme representations themselves. As a consequence, violations of harmony should not directly follow from acoustic-phonetic properties of the disharmonic vowels. For instance, one could hypothesize that disharmony between two vowels correlates with their acoustic distance: The larger this distance, the 'more disharmonic' the vowel sequence (equating harmony with a kind of least-effort principle). Although harmony may have an 'evolutionary' source in vowel-to-vowel co-articulation (cf.

Fowler 1983; Ohala 1994a, 1994b; Beddor, Krakow, and Lindemann 2001), we assume that in Turkish, this has become grammaticalized into a phonological principle. The language-specific grammaticalization of vowel-to-vowel co-articulation would predict that harmony violations predominantly emerge from language-specific feature oppositions or constraint violations (based on a particular constraint ranking). One can imagine that a vowel sequence A is 'more disharmonic' than a vowel sequence B if A involves more featural oppositions than B. Consider the Turkish vowels [ɯ], [œ], and [ɛ] that are in close vicinity in the acoustic vowel space (Figure 1, panel B). The sequence [ɯ]-[œ] differs in all possible featural dimensions, unrounded-round, back-front, and high-low. In contrast, the sequence [ɛ]-[œ] only differs in the opposition of unrounded-rounded (Table 3). Regarding Turkish vowel harmony, the first sequence violates both place (back-front) and roundedness (unrounded-rounded) harmony, while the second sequence only violates roundedness harmony. If one considers [œ] to be in non-initial position in a word then both sequences also violate the *RoLo constraint. What are the perceptual consequences of illicit Turkish vowel sequences of the kind illustrated above? Would the disharmony of vowel sequences be independent of their embedding in words? And how would the interaction of *RoLo with S-Ident (F) affect the perception of disharmonic sequences that differ in featural distance or in acoustic distance? Finally, do perceptual correlates of harmony violations reflect the fact that certain violations occur more frequently than others?

An ideal neurophysiological measure to address these questions is the so-called Mismatch Negativity (MMN). It is an auditory evoked event-related response of the brain, automatically and pre-attentively elicited whenever there is a discriminable change between auditory stimuli or a violation of an abstract rule extracted from the auditory stimulus material (Näätänen et al. 1997; Winkler 2007). The MMN is commonly observed in so-called passive-oddball paradigms where participants are presented with series of repetitious sounds (*standards,* e.g., the vowel [o]) that are followed by rare sounds (*deviants,* e.g., the vowel [e]). Deviants trigger the MMN response due to the acoustic difference between standards and deviants. Measured by electroencephalography (EEG), it is observed as negative deflection starting at around 150–200 ms after stimulus onset. In magnetoencephalographic (MEG) recordings, i.e., when the magnetic field induced by neuronal electric activity is measured, the MMN surfaces as difference in root-mean square amplitude of the magnetic field strength from a set of selected recording channels centered over the auditory cortex. Amplitudes are usually larger for deviants than for standards. Note that the advantage of MEG over EEG for MMN studies is that MEG allows for a more accurate localization of the underlying source activity in human cortex than EEG. Further, MEG requires less preparation for the participants. The MMN is measured in terms of amplitude (difference between deviant and standard response) and peak latency (the peak of the difference wave form obtained by subtracting the averaged standard responses from the averaged deviant responses).

Besides reflecting acoustic changes, the MMN is further modulated by language-specific information regarding phonemes (Näätänen et al. 1997), affixes (Shtyrov and Pulvermüller 2002a) and words (Shtyrov and Pulvermüller 2002b). For instance, the MMN to the change from [o] to [e] would be larger if both vowels belonged to the native vowel inventory of the listeners than if one or both vowels were non-phonemic in the listener's language. Finally, the MMN is sensitive to language-specific phonotactic constraints (Dehaene-Lambertz et al. 2000; Bonte, Mitterer, Zellagui, Poelmans, and Blomert 2005; Steinberg, Truckenbrodt, and Jacobsen 2010a, 2010b) and vowel harmony (Aaltonen et al. 2008). Thus, using different and disagreeing vowels as standards and deviants provides an elegant diagnostic for disharmony effects between these respective standards and deviants. Furthermore, the MMN provides a very temporally accurate measure for the investigation of the time course of speech perception at very early, pre-lexical stages. Depending on the sampling frequency, the temporal resolution of this method is one millisecond (or better).

So far, there are only a few MMN studies on the perception of vowel harmony. Aaltonen et al. (2008) investigated vowel sequences in Finnish and Estonian. Finnish shows place harmony between vowels, disallowing the co-occurrence of front (coronal) and back (dorsal) vowels in bisyllabic words (Suomi, McQueen, and Cutler 1997). Place features spread from the first syllable rightwards to the following vowel(s). Estonian, a language closely related to Finnish, does not show this type of harmony. Aaltonen and colleagues predicted that, therefore, Finnish and Estonian listeners would differ in accepting the pseudoword [tækæ̲], where [æ̲] is a non-prototypical vowel in-between front [æ] and back [a]. Put differently, [æ̲] is a central vowel that neither falls in the front nor the back category in either Finnish or Estonian.

For Finnish speakers, the change of the final vowel towards back [a] violates vowel harmony, while it does not for Estonian speakers. By contrast, both Finnish and Estonian speakers should similarly accept the pseudo-word [tækæ] with two front vowels. These predictions were tested by presenting both kinds of pseudowords in a passive oddball paradigm, where the unchanged coronal pseudo-word [tækæ] was presented frequently (as standard) and the changed pseudo-word [tækæ̲] was interjected rarely (as deviant). The change between standard and deviant resulted in an MMN for both groups of listeners. However, the MMN was larger for the Finnish listeners than for the Estonian listeners. Aaltonen and colleagues (2008) suggested that this outcome reflected the long-term representation of the abstract harmony rule in Finnish, adding a harmony violation on top of the acoustic difference between [æ] and [æ̲] that resulted in a larger MMN. That is, the larger MMN is the result of the combination of two effects: the acoustic effect common to both groups and the grammatical effect restricted to the Finnish speakers.

While Aaltonen et al. (2008) focused on a cross-linguistic comparison, we are interested in different harmony violations within one language, viz. Turkish. If har-

Table 5. *Pairs of contrast, distributed over standard and deviant position, for Turkish MMN experiment, and number of vowel co-occurrence in the first two syllables of Turkish roots (frequency counts from the Turkish Electronic Living Lexicon, TELL). The column Violation indicates whether the violation of the highest-ranked constraint is symmetrical or asymmetrical between standard-deviant reversal.*

Standard-deviant sequence	Violation	Acoustic distance	Occurrence
[ɯ] – [œ]	symmetric (place)	small	2
[œ] – [ɯ]			0
[ɛ] – [œ]	asymmetric (*LoRo)	large	5
[œ] – [ɛ]			141

mony is in fact independent of lexical entries on some level of processing, as the study by Aaltonen et al. (2008) suggests, we expect to find harmony effects on the MMN even in sequences of single vowels. For that purpose, we contrasted a subset of Turkish vowels such that pairs of comparisons differed in acoustic and featural distance as well as in the type of violations. The set of contrasts is given in Table 5 and elucidated in more detail below. We assume that each vowel sets up a prediction for the following vowel in the sequence that is consistent with Turkish vowel harmony.

The selection of the three vowels [ɯ], [œ], and [ɛ] seemed ideal to us, since they allow us to dissociate between acoustic distance and featural distance. Crucially, the featural distance between [ɯ] and [œ] is maximal, given differences in all three dimensions: height, place, and roundedness. Yet the acoustic distance between these vowels is minimal. On the other hand, [œ] and [ɛ] differ only in roundedness, while their acoustic distance is considerably larger than the distance between [ɯ] and [œ]. Thus, the selection of these vowels exemplifies that acoustic distance does not necessarily translate into featural distance. Finally, the vowels [ɯ] and [œ] are disharmonic in either direction (i.e., in assuming [ɯ] or [œ] being the first vowel in a word, and [œ] or [ɯ] the respective second vowel). Note that we consider this a symmetrical situation on the basis of the highest-ranked constraint Ident-S (Place) that is violated in both cases. On the other hand, [œ] and [ɛ] violate the highest-ranked *RoLo constraint if [ɛ] precedes [œ] but not if [œ] precedes [ɛ]. Therefore, the sequence [œ]-[ɛ] would be an accepted exception of roundedness harmony, and based on the highest-ranked constraint here, we consider the reversal of the vowel sequences as asymmetric (see Tables 4, 5, 8).

Our expectations regarding the MMN in response to vowel deviants in the second position of the respective sequences are as follows. First, due to the phonological nature of harmony violations, the acoustic distance between standard and deviant vowel should not modulate the MMN. Second, the sequences [œ]-[ɯ] and [ɯ]-[œ] comprise a place and rounding harmony violation, and an additional *RoLo violation for the [ɯ]-[œ] sequence. If in fact the constraint on place harmony is ranked highest, it should be similarly violated in both conditions, and

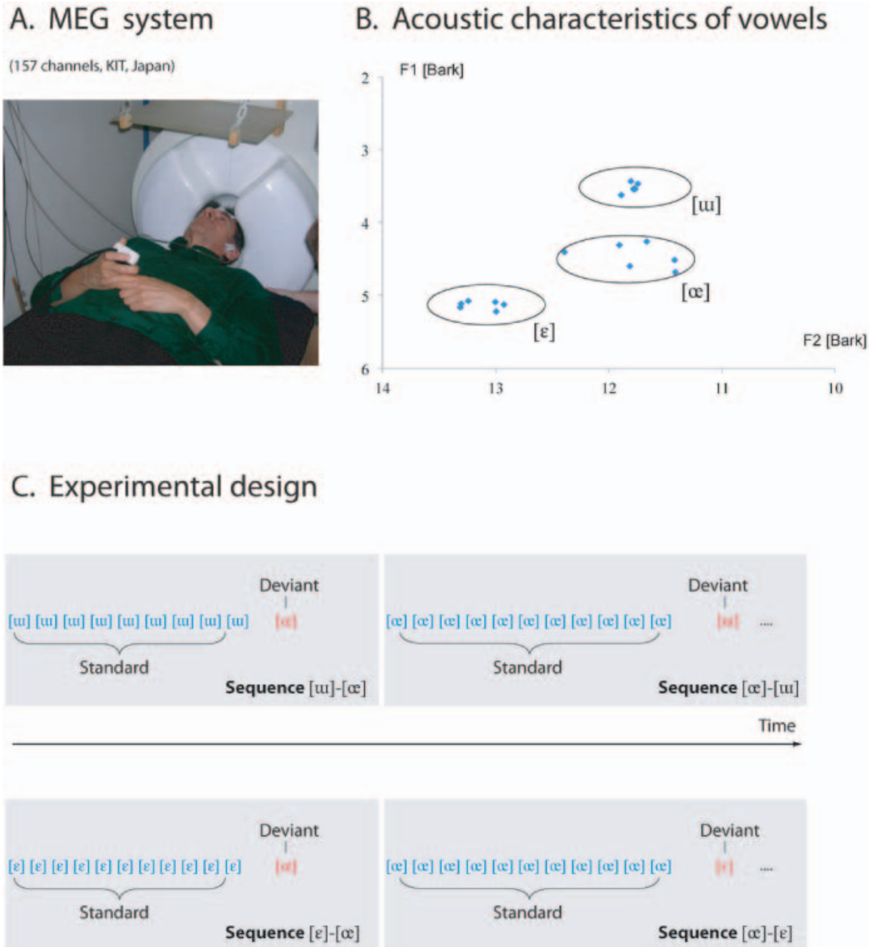

Figure 1. *MEG system (panel A); acoustic properties of stimulus vowels in the F1/F2 space in Bark (panel B); experimental design of the Turkish MMN study, passive oddball (panel C).*

therefore produce symmetric MMNs. In contrast, the sequences [ɛ]-[œ] and [œ]-[ɛ] do not violate the place harmony constraint. If *RoLo is ranked above the roundedness harmony constraint, the sequence [ɛ]-[œ] ought to elicit a larger response than the sequence [œ]-[ɛ], since the former, but not the latter, violates *RoLo. We tested these predictions in a Magnetoencephalographic (MEG) MMN study (cf. Figure 1, panel A) in which we presented standard-deviant trains involving the three Turkish vowels [ɯ], [œ], and [ɛ] with the four contrasts illustrated above (cf. Figure 1, panel C).

3.1. *Materials*

We recorded 10 exemplars of each of the three vowels [ɯ], [œ], and [ɛ] from a native Turkish speaker who produced the stimuli in the carrier-sentence corresponding to the English frame "I will say _ again". He was instructed to slowly and clearly pronounce the vowels, with an audible pause between the preceding and following context. All vowel exemplars were digitized at 44.1 kHz, with an amplitude resolution of 16 bit, using a Røde NT1-A microphone. Subsequently, 6 exemplars with similar pitch contours were selected, and steady-state parts of the vowels (200 ms) were cut out of original recordings using the phonetic sound software PRAAT (Boersma and Weenink 2009). Onsets and offsets were faded by 25 ms cosine-squared ramps. Average intensities were normalized to 70 dB in order to guarantee auditory delivery at 60 dB SPL in the MEG scanner. First and second formant values of the vowels (in Bark) are illustrated in Figure 1, panel B. Euclidean distances between the vowels [ɯ] and [œ] (small distance) and between the vowels [œ] and [ɛ] (large distance) were calculated on the basis of the first three formants (in Bark). The distances differed significantly (small: 1.1 Bark, standard deviation: 0.22; large: 1.7 Bark, standard deviation: 0.33; $t = 3.71$, $p < 0.01$).

3.2. *Design*

Vowel stimuli were organized in a passive standard/deviant many-to-one oddball paradigm (Phillips et al. 2000; Winkler et al. 1999, cf. Figure 1, panel C). The vowels [ɯ] and [œ], as well [œ] and [ɛ], were distributed over four blocks (sequences) in which they occurred in either standard ($p = 0.875$, $N = 700$) or deviant position ($p = 0.125$, $N = 100$, see Table 4). For instance, the sequence [ɯ]-[œ] was tested in block one where [ɯ] was the standard and [œ] the deviant. The number of standards between two deviants varied randomly in each block in order to prevent strategic processing. Thus, on average, there was a deviant after seven preceding standards. The inter-stimulus intervals (ISIs) between standards and deviants, and deviants and standards pseudo-randomly varied between 500 and 1000 ms. This was done in order to prevent participants from entraining to the rhythm of presentation, which could mask MMN effects. Each block contained a total of 800 trials and lasted approximately 15 minutes. The block order was counter-balanced across subjects. Trials were presented binaurally at a comfortable listening level of about 60 dB SPL with the software package PRESENTATION (Neurobehavioral Systems).

3.3. *Subjects and procedure*

Fourteen native speakers of Turkish without any auditory or perceptual impairments (mean age 30, $SD = 9.7$, 36% females) participated in the study that was approved by the ethics committee of the University of Maryland. Subjects were paid $15 for their participation. All participants provided informed written consent and were strongly right-handed (> 80%) on the Edinburgh Handedness Inventory (Oldfield 1971).

During MEG recording and stimulus presentation, participants lay supine in a magnetically shielded chamber containing a whole-head MEG scanner with 157 axial-gradiometers (Kanazawa Institute of Technology, Kanazawa, Japan). Magnetic fields were recorded at a sampling rate of 500 Hz, with an online 200 Hz low-pass filter and a 60 Hz notch filter. Auditory stimuli were delivered binaurally via Etymotic ER3A insert earphones. Earphones were calibrated to have a flat frequency response between 50 Hz and 4000 Hz within the shielded room, thus covering the perceptual space for the first three formant frequencies of the test stimuli. Prior to the main experiment, participants completed a tone perception pre-test that served as a basis for the selection of channels of interest. The tone experiment should reliably elicit so-called N1m/M100 responses from temporal regions, i.e., from the auditory cortex (Näätänen and Picton 1987). The auditory cortex is one of the main sources of the MMN response elicited by auditory stimuli (Näätänen and Alho 1997). During this tone task, subjects were instructed to silently count high (1000 Hz) and low (250 Hz) sinusoidal tones (~300 total), auditorally presented in pseudo-random order. Only participants with a reliable bilateral M100 response were included in further analyses, resulting in the exclusion of one participant, thus leaving 13 participants for the subsequent statistical analyses.

During the main experiment, participants passively listened to standard-deviant sequences that were presented in blocks, as illustrated in Table 4. The use of six acoustically different and naturally produced tokens for each vowel ensured that standards could activate more abstract representations, such that the standard presentation could tap into underlying phonological and not merely acoustic/phonetic representations (Phillips et al. 2000). At random positions within each block, participants were played disyllabic Turkish words in order to reduce environmentally induced influences from American English (cf. Hay, Warren, and Drager 2006). Between blocks, there was a short break during which participants were asked whether they remembered the Turkish words. In addition, the experimenter communicated with the participants in Turkish.

Participants watched a silent movie during the passive listening task in order to reduce eye movements and maintain an awake state. The movie was projected onto a screen approximately 15 cm above the participants. Including experiment preparation and the tone pre-test, the entire experiment lasted approximately 90 minutes.

3.4. *Data analysis*

Environmental and MEG scanner noise was removed from the raw data using a multi-shift PCA noise reduction algorithm (de Cheveigné and Simon 2007, 2008). In the next step, each individual event-related response to standards and deviants was examined for artifacts. Artifact rejection was done by visual inspection. Amplitudes higher than 3 pT (pico-Tesla) or epochs with more than 3 consecutive eye blinks led to the exclusion of the corresponding epoch. This procedure resulted in the exclusion of no more than 15% of standards or deviants.

After artifact rejection, we randomly selected 100 standards for each condition and subject, in order to match the number to the number of deviants. Note that the many-to-one passive oddball design resulted in seven times more standards than deviants for one experimental condition. Standards and deviants responses were averaged, separately for each condition and subject. Averaged epochs consisted of a 100 ms pre-stimulus and 500 ms post-stimulus interval. They were baseline-corrected over the 100 ms pre-stimulus interval and band-pass filtered between 1 Hz and 30 Hz (using a Hamming window). Base-line correction is necessary to eliminate any potential differences that are not stimulus-related while band-pass filtering ensures that low-frequency and high-frequency brain activity, potentially masking the MMN response, is reduced.

The 10 strongest channels per hemisphere, obtained from the tone pre-test, were selected for subsequent amplitude and peak latency analyses.

On the basis of the grand average (i.e., the average of standards/deviants in each condition across all participants), deviants most prominently differed from standards in a time window from 120 to 220 ms post stimulus onset, and in a later window, between 330 and 380 ms post onset. We attributed the first window to the pre-attentive MMN, as usually found between 100 and 300 ms (Näätänen and Alho 1997), while the second window seems to correspond to the phonological mismatch negativity (PMN; Connolly and Phillips 1994; Praamstra, Meyer, and Levelt 1994). This response is said to reflect phonological processing and may also index phonological expectancies. Praamstra et al. (1994) used an auditory lexical decision task with priming and recorded EEG responses. The responses to rhyming prime-target pairs showed less negative deflections in a time frame between 450 and 700 ms post stimulus onset, compared to unrelated prime-target pairs. On this basis, they interpreted the more negative deflection in the control condition (where there was no phonological relation between prime and target) as an index of phonological mismatch.

For the statistical analyses, we calculated the root-mean squared (RMS) magnetic field strength over the selected 10 channels in each hemisphere for the averaged standard and deviant responses for each condition and subject, as is commonly done in MMN studies (e.g., Inouchi et al. 2004). These values were analyzed separately for each time-window of interest in Mixed Effect Models with *subject* as random effect (Pinheiro and Bates 2000; Baayen 2008) and *hemisphere* (left/right), *position* (standard/deviant), and *vowel* ([ɯ], [œ], [ɛ]) as fixed effects.

MMN latencies were calculated from the difference waveforms of acoustically identical stimuli in deviant and standard position (i.e., deviant – standard, e.g., deviant [œ] – standard [œ]). From these difference waveforms, peak latencies between 120 and 220 ms were selected by visual inspection. The latency model comprised the fixed effects *hemisphere* (left/right) and *distance* (acoustic distance large/small, cf. Table 5).

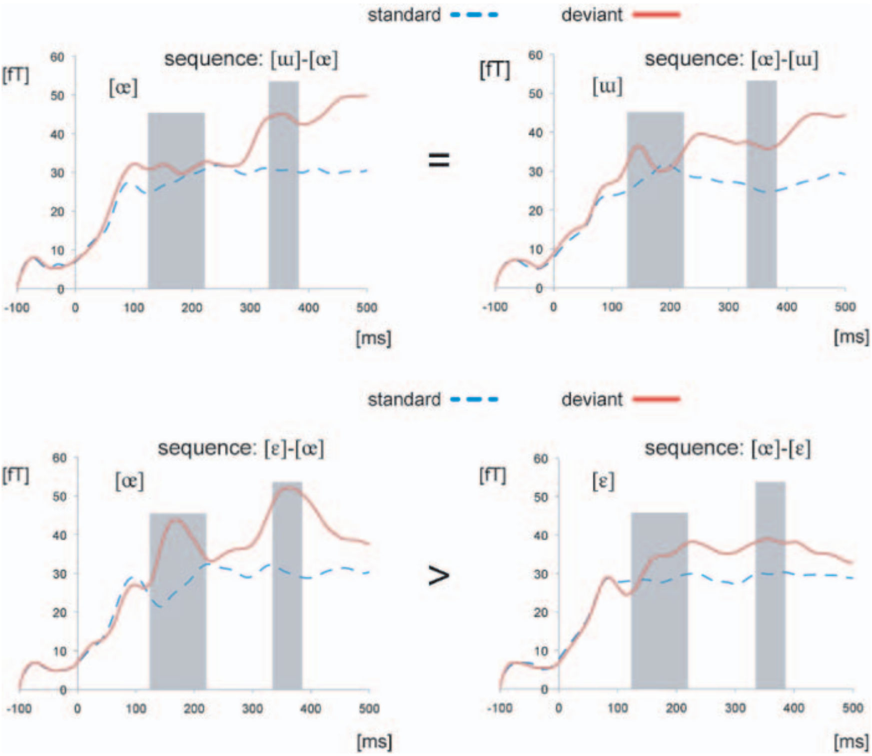

Figure 2. *Grand average root mean square (RMS) responses in the four conditions of the MMN experiment on Turkish vowels. The RMS is based on the 10 strongest channels in the left and in the right hemisphere, as determined by an auditory screening test. Selected time windows for the MMN (first) and PMN (second) are marked in grey. Conditions are presented in the order introduced in Table 5. Each graph shows the averaged response to the standard (dashed line) and the deviant (solid line) of the same vowel.*

3.5. *Results*

The grand average of standard and deviant responses across participants for each condition (standard-deviant sequence) is illustrated in Figure 2. Responses seem of similar magnitude for the sequences [ɯ]-[œ] and [œ]-[ɯ], but crucially, the deviant response in the sequence [ɛ]-[œ] has a higher amplitude than in the sequence [œ]-[ɛ]. This holds for both early and late time windows.

The statistical analysis of amplitude in the MMN time window showed a main effect of *position* ($F(1,180) = 16.13$, $p < 0.01$), reflecting higher amplitudes for deviants than for standards. Note that this reflects our baseline against which we compare lower or higher MMN amplitudes. Further, there was an interaction of *position* × *vowel* ($F(3,180) = 4.01$, $p < 0.01$). MMNs as difference between devi-

Table 6. *MMN mean amplitudes and peak latencies in the four experimental conditions (SEM = standard error of the mean).*

Standard-deviant sequence	Amplitude	SEM	Latency	SEM
[ɯ] – [œ]	3.1	2.94	166.31	4.06
[œ] – [ɯ]	1.9	2.72	166.87	4.09
[ɛ] – [œ]	19.0	3.42	173.13	3.97
[œ] – [ɛ]	7.2	2.90	176.21	3.08

ant and standard responses to the same vowel differed between the [ɛ]-[œ] and the [œ]-[ɛ] sequence ($t = 2.10$, $p < 0.05$), but not between the [ɯ]-[œ] and the [œ]-[ɯ] sequence ($t = 0.9$, $p = 0.38$). This indicates a response asymmetry between the sequence [ɛ]-[œ] involving the *RoLo constraint violation, and the sequence [œ]-[ɛ] where the *RoLo constraint legitimized the roundedness harmony violation. We further compared the sequences [ɯ]-[œ] and [ɛ]-[œ] with the same deviant vowel [œ], and the sequences [œ]-[ɯ] and [œ]-[ɛ] with the same standard vowel [œ]. The MMN in the first comparison differed significantly between conditions ($t = 2.76$, $p < 0.01$), showing higher amplitudes if [œ] was preceded by [ɛ]. The second comparison showed no significant MMN differences ($t = 1.58$, $p < 0.12$).

The PMN analysis similarly showed an effect of *position* ($F(1,180) = 47.75$, $p < 0.001$). Deviant responses had higher amplitudes than standard responses. There was an additional effect of *vowel* ($F(3,180) = 4.85$, $p < 0.01$) and a marginally significant interaction *position* × *vowel* ($F(3,180) = 2.30$, $p = 0.07$). The PMN amplitude of the sequence [ɛ]-[œ] was larger than the PMN amplitude of the reverse sequence [œ]-[ɛ] ($t = 2.37$, $p < 0.05$), paralleling the pattern of the earlier MMN. Also, we found that PMNs were significantly larger in the sequence [ɛ]-[œ] than in the sequence [ɯ]-[œ] ($t = 6.10$, $p < 0.001$). In contrast, there were no such differences between the sequences [œ]-[ɯ] and [œ]-[ɛ] ($t = 0.45$, $p = 0.48$).

The latency analysis revealed a significant *distance* effect ($F(1,81) = 4.61$, $p < 0.05$), arising from earlier MMN peaks in the sequences [ɯ]-[œ] and [œ]-[ɯ] with a small acoustic, but a larger featural distance between standard and deviant vowels (MMN peak larger distance: 167 ms; MMN peak small distance: 175 ms; cf. Table 6). The effect was slightly left-lateralized, as indicated by a trend for an interaction of *hemisphere* × *distance* ($F(1,81) = 2.10$, $p = 0.15$).

4. Discussion

The results of this MMN study on Turkish vowel harmony violations showed several important aspects of abstract phonological rule or constraint representations and their neurobiological reflections. First, the asymmetry between the sequences [ɛ]-[œ] and [œ]-[ɛ] seems to emerge from the violation of the *RoLo constraint without the violation of the higher-ranked Ident-S (place). Despite the same acoustic distance between the two vowels [œ] and [ɛ] in these conditions, MMN amplitudes were significantly larger if the deviant [œ] was preceded by the standard [ɛ]. We propose that the vowel sequence [ɛ]-[œ] was subject to the *RoLo constraint, penalizing low round vowels if they are not in the first syllable, or, in this case, in first (standard) position of the sequence. The constraint was thus not violated in the sequence [œ]-[ɛ], where the resulting MMN solely indicated the acoustic vowel change. As a consequence, the response was significantly smaller. Therefore, it seems that the violation of the *RoLo constraint enhanced the MMN, irrespective of the acoustic bases of the vowel difference.

Note that a pure acoustic explanation of our results would predict that the MMN varies as a function of the acoustic distance between standard and deviant vowel. This is in fact a common interpretation of the MMN for non-speech stimuli (cf. Näätänen, Paavilainen, Rinne, and Alho 2007). As can be seen from our analyses, the distance between [ɛ] and [œ] (and vice versa, between [œ] and [ɛ]) is significantly larger than the distance between [œ] and [ɯ]. Thus, under an acoustic analysis, both large distance conditions should have yielded a similarly larger MMN compared to the sequences [ɯ]-[œ] and [œ]-[ɯ] with a small acoustic distance. In order to assess the independence of the MMN effects from the acoustic distance between standard and deviant vowel, we deliberately chose contrasts involving smaller and larger acoustic distances (as measured by Euclidean distances in acoustic space determined by the first three formants). We therefore also compared MMNs between conditions sharing the same standard [œ] and between conditions sharing the same deviant [œ]. For both MMN and PMN in the 'same-deviant' comparison, mismatch amplitudes were larger if the vowel sequence violated the *RoLo constraint in the acoustically more distant condition. At the same time, however, MMN and PMN did not differ between the 'same standard' conditions, although the acoustic distance between standard and deviant was larger in the [œ]-[ɛ] sequence than in [œ]-[ɯ] sequence. Thus, MMN amplitudes did not solely depend on the acoustic properties of standard and deviant, but were modulated by more abstract, phonological constraints operating on the respective sequence of vowels, consistent with a composite view of the MMN as a combination of acoustic and grammatical effects.

Second, the observation of a late negativity between 300 and 400 ms post stimulus onset suggests the presence of the so-called Phonological Mismatch Negativity (PMN; Connolly and Phillips 1994; Praamstra et al. 1994). This component has been found independently of input modality and has been interpreted as reflecting phonological processing and phonological expectancies. In our case, it backs up the assumption that the vowel sequences in fact triggered phonological analyses as if these vowels were embedded in (lexical) words. On the basis of the *RoLo constraint, the deviant [œ] (violating *RoLo in the sequence) was clearly less expected than the deviant [ɛ] (not violating *RoLo). Indeed, the asymmetric MMN pattern was paralleled in the time window of the PMN between 330 and 380 ms after vowel onset. Here, deviant [œ] preceded by standard [ɛ] elicited a stronger PMN than deviant [ɛ] preceded by standard [œ]. Further experiments embedding these sequences in Turkish pseudo-words could potentially confirm these results with other measures (such as delayed N1m responses to vowels with constraint violations, similar to what Flagg, Cardy, and Roberts (2005) found for cases of anomalous nasalization in English sound sequences).

A similar late negativity in an MMN design was found by Aaltonen et al. (2008). Apart from their pseudoword condition, they also contrasted single vowels, i.e., standard [æ] with the more central deviant [æ]. There, they found a larger negativity for Finnish listeners at around 400 ms after stimulus onset. Intergroup differences in MMN magnitude, on the other hand, only showed a trend in that Finnish listeners produced a stronger MMN response than Estonian listeners. The difference between their experiment and our study, however, is that their deviant was a non-prototypical vowel exemplar and could potentially be mapped onto a front or a back vowel. In our study, we always used unchanged and naturally produced vowel exemplars, such that ambiguous classifications were unlikely. The ambiguity in mapping the deviant vowel to either a front or a back vowel in Aaltonen et al.'s (2008) experiment may have attenuated the MMN effects, elicited by vowel harmony violations for the Finnish listeners. The pseudo-word context may have better disambiguated the vowel, or, a more likely conjecture, the MMN response to the second vowel in the deviants may have involved a more phonological and categorical processing. As a consequence, intergroup differences were more clear-cut in these cases.

The view that the MMN is sensitive to sequential aspects of standard-deviant presentation despite the many-to-one ratio between standard and deviant is supported by findings that suggest the existence of sequence detectors (Pulvermüller 2003). While 'sequences' there refers to consecutive words, given the existence of phonotactic conditions sequence detectors must work on the basis of single phonemes, too. Note that such an approach to vowel harmony is compatible with the view that harmonic patterns emerge from co-occurrence probabilities of particular vowels (cf. Cole 2009). From a brain's perspective, neuronal cell assemblies responding to individual, different vowels in isolation may form a unit in responding to sequences of these vowels. These units may become stronger, and cell assemblies connect tighter, the more often (i.e., the more probable) the specific vowel sequence occurs in the speech input (cf. Hebb 1949).

However, a pure frequency-of-occurrence account does not provide a full explanation for our data. According to the Turkish Electronic Living Lexicon, an online database with about 30,000 words (TELL, http://linguistics.berkeley.edu/TELL/), the frequency of occurrence of the three vowels in Turkish roots varies considerably (counts [ɛ]: 6092; [ɯ]: 2095; [œ]: 625). It is known that the MMN increases with a decrease of deviant probability within an experimental setup for non-speech sounds (Näätänen et al. 2007). If one equates deviant probability with frequency of occurrence in the respective language, the frequency approach would correctly predict higher MMN amplitudes for the deviant [œ] in the [ɛ]-[œ] sequence due its low frequency of occurrence in Turkish roots, and lower MMN amplitudes in the [œ]-[ɛ] sequence with the higher frequent deviant [ɛ]. However, this explanation should hold *a fortiori* for the comparison between the sequences [ɯ]-[œ] and [œ]-[ɯ]. This comparison did not yield an amplitude asymmetry.

We are aware that non-significant differences between conditions may possibly result from a small number of participants. However, our population size is typical for studies in the MMN literature, and compensated for by many repetitions of the individual standard and deviant stimuli.

Another possible account in order to explain the observed MMN pattern is to invoke co-occurrence frequencies of the vowels in each condition. Based on a frequency count in TELL, the sequence [œ]-[ɛ] in Turkish roots has the highest frequency, and therefore, the highest probability to occur (cf. Table 5). According to the findings of Bonte et al. (2005), deviants with a high-probability phonotactic pattern ought to elicit stronger MMN responses than deviants with a low-probability pattern. Thus, we would predict the largest MMN response for the sequence [œ]-[ɛ]. Our data, in contrast, showed the opposite pattern. Even if the phonotactic probability account would not make a directional claim regarding the size of the MMN depending on the phonotactic probability in the stimulus material, one would expect to find similar responses in the conditions with similar vowel sequence frequencies (first three sequences; cf. Table 5). Again, our findings do not support this assumption.

Finally, our expectation for symmetric MMN responses in the [ɯ]-[œ] and [œ]-[ɯ] sequences relied on the symmetric violation of the highest-ranked Ident-F (Place) constraint. If this constraint is not violated, the next-highest relevant constraint is *RoLo, accounting for the amplitude asymmetry between the [ɛ]-[œ] and [œ]-[ɛ] sequences (Table 8). The MMN for the deviants [œ] and [ɯ] in the sequences [ɯ]-[œ] and [œ]-[ɯ] is similarly affected by the place disharmony with respect to the corresponding standards. Constraint violations hence do not seem to have additive effects on the MMN amplitude: Even though *RoLo was violated in the [ɯ]-[œ] sequence, but not in the [œ]-[ɯ] sequence, the MMN amplitudes were similar. We propose that this reflected the presence of a higher-ranked constraint whose violation in both sequences modulated the MMN response. In this respect, our MMN amplitude pattern can be accounted for by an OT approach (Table 8). The latency pattern, on the other hand, appears to be better accounted for by an underspecification approach. This is elucidated below.

Previous MMN research has shown that MMN latency similarly indexes the amount of mismatch, as does MMN amplitude (Lang et al. 1990; Winkler, Tervaniemi, and Näätänen 1997; Näätänen, Jacobsen, and Winkler 2005). Lang et al. (1990) and Winkler et al. (1997) have provided evidence that MMN latency variations correlate with the magnitude of stimulus changes. Shorter latencies corresponded to larger changes. Regarding more abstract stimulus attributes, Eulitz and Lahiri (2004) found MMN latency to be a good indicator for feature mismatches between standard and deviant. In their single vowel study, they looked at German dorsal

Table 7. *Standard and deviant feature relations, following an underspecification approach.*

Standard-deviant sequence	Standard features	Deviant features	Mismatch	Latency
[ɯ] – [œ]	[dor] [–]	[cor] [low]	place	early
[œ] – [ɯ]	[–] [low]	[dor] [high]	height	
[ɛ] – [œ]	[–] [low]	[cor] [low]	none	late
[œ] – [ɛ]	[–] [low]	[cor] [low]	none	

(back) [ɔ] and coronal (front) [œ] in standard and deviant position of a passive oddball MMN design. Their experiment was set up to test the hypothesis of coronal underspecification (cf. Lahiri and Reetz 2002). The rationale was to expect a place feature mismatch in the [ɔ]-[œ] sequence. There, the standard [ɔ] was assumed to activate its fully specified dorsal (back) representation through the repetitious presentation of acoustically varying vowel exemplars (cf. Näätänen et al. 1997; Phillips et al. 2000). The deviant, on the other hand, supplied the mismatching coronal surface feature. In contrast, the coronal standard in the reversed sequence [œ]-[c] was supposed to tap into a featurally underspecified representation, such that the dorsal deviant did not supply a mismatching feature. Eulitz and Lahiri's results confirmed this prediction. Coronal deviants did not only elicit larger MMN amplitudes, but crucially also earlier MMN peak latencies.

The underspecification-based interpretation is also valid for our data, if we follow Kabak (2007) in assuming that [cor] and [high] are not specified in Turkish vowels (cf. Table 3). For the sequences [ɯ]-[œ] and [œ]-[ɯ] in our experiment, we would expect to find height and place mismatches, as illustrated in Table 7. If [œ] is the standard, and [low] (but not [high]) is represented underlyingly, the coronal vowel will activate a representation underspecified for place, but specified for height. The deviant [ɯ] will then provide a mismatching height feature, since [high] will still be extracted from the incoming signal. At the same time, [dor] is not a mismatch for the underspecified place representation of the standard. In the reverse case, [ɯ] will activate its underlying [dor] representation, but height is underspecified. The corresponding deviant [œ] provides a mismatching coronal surface feature.

As for height, [low] does not mismatch with the underspecified representation of the standard. Thus, the vowel oppositions in the first two sequences involve one feature mismatch in each direction.

This does not hold for the other two sequences. In the sequence [ɛ]-[œ], the standard [ɛ] should activate a representation underspecified for place, but specified for [low]. The deviant [œ] provides the surface features [cor] and [low], none of which mismatch with the standard representation. Similarly, in the sequence [œ]-[ɛ], standard [œ] taps into a place-underspecified, [low] representation, for which the deviant [ɛ] does not provide any mismatching features (being [cor] and [low]).

Note that differences in labiality should never lead to mismatches, following the match/mismatch principles of Lahiri and Reetz (2002). Labiality for vowels is a secondary place of articulation. In contrast, coronality and dorsality are mutually exclusive, and in the matching evaluation, a surface coronal feature mismatches with an underlying dorsal feature. However, both coronal (front) and dorsal (back) vowels can be labial (rounded). A surface labial feature (e.g., from [œ]) does not mismatch with the non-specified labial feature of an unrounded vowel (e.g., [ɛ]). Thus, the surface absence of the secondary place feature [lab] (= labial) does not lead to a mismatch, while primary place features (Scharinger et al. 2011) and laryngeal features (Hwang, Monahan, and Idsardi 2010) may show a different pattern.

The mismatch/nomismatch relations between standard and deviant vowels in the sequences [ɯ]-[œ] and [œ]-[ɯ] versus the sequences [ɛ]-[œ] and [œ]-[ɛ] align with the latency effect between these conditions. In particular, the sequences [ɯ]-[œ] and [œ]-[ɯ] elicited significantly earlier MMN peak latencies than the sequences [ɛ]-[œ] and [œ]-[ɛ]. If earlier MMN peak latencies indeed reflect feature mismatches, our experiment provides neurobiological evidence for vowel underspecification in Turkish, as envisaged by Kabak (2007). Note, however, that the asymmetry between [ɛ]-[œ] (larger amplitude) and [œ]-[ɛ] (smaller amplitude) must still be explained by violations of the *RoLo constraint. As laid out above, we assume that a violation of *RoLo results in a larger MMN amplitude.

Approaches that assume full feature specifications for vowels would not necessarily differ in their qualitative predictions from the underspecification account presented above. These approaches would assume that a three-feature difference between standard and deviant (as is the case for [ɯ]-[œ] and [œ]-[ɯ]) elicited an earlier MMN than a one-feature difference (as in [ɛ]-[œ] and [œ]-[ɛ]). Again, a full feature specification approach would have to explain the amplitude asymmetry in the [ɛ]-[œ]/[œ]-[ɛ] comparison with the *RoLo constraint.

Altogether, underspecification seems to be a feasible approach for Turkish vowel harmony. Not only does it account for neurophysiological data on harmony violations, as presented here, but it also offers a unified treatment of harmony, epenthesis, and hiatus processes in the phonology of Turkish (Kabak 2007).

This being said, our MMN latency data could also be modeled by an OT approach as illustrated in Table 8. The latency of the MMN appears to primarily depend on the violation of the highest-ranked constraint.

The sequences [ɯ]-[œ] and [œ]-[ɯ] yield a symmetrical violation of S-Ident (Place), since standard and deviant vowels do not agree in place of articulation. Since this constraint outranks *RoLo, the violation of the co-occurrence constraint is less relevant than in the sequence [ɛ]-[œ], where there is no violation of S-Ident (Place). Thus, it seems reasonable to assume that the violation of a higher-ranked constraint correlates with an earlier *MMN latency*, while differences in *MMN amplitude* correlate with the violation versus non-violation of *RoLo if no higher-ranked constraint is violated. Under this assumption, it is not merely the number of

Table 8. *Sketch of OT tableau for vowel sequences in the four experimental conditions and related MMN pattern.*

Standard-deviant sequence	S-Ident (place)	*RoLo	S-Ident (round)	MMN
[ɯ] – [œ]	*!	*	*	symmetric
[œ] – [ɯ]	*!		*	
[ɛ] – [œ]		*!		asymmetric
[œ] – [ɛ]			*	

constraint violations, but also the constraint ranking which accounts for the MMN pattern in our experiment. For this reason – other complications set aside – OT offers an alternative way of modeling MMN data and is clearly a future endeavor worthy to pursue. Further, the comparison of these two modeling approaches – underspecification and OT – shows that they are not necessarily mutually exclusive or entirely contradicting.

One potential problem with our experiment is that we have no independent means in an MMN design to assess whether listeners treated the vowel sequences as belonging to the word domain. Our implicit assumption is that the MMN pattern reflects harmony violations as if they would have appeared in a word. If, in contrast, the word domain did not play a role for participants' responses, the MMN pattern may reflect a more abstract phonotactic principle, but not vowel harmony proper. Our hypothesis (that clearly needs supporting evidence from future research) is that a language with vowel harmony exerts influences on speech processing at very early pre-lexical and automatic stages, as can be indexed by ERP measures, such as the MMN. Previous research suggests that these early influences come from language-specific phonotactic constraints (Aaltonen et al. 2008; Dehaene-Lambertz, Dupoux, and Gout 2000; Dupoux et al. 2001), and we take vowel harmony to be based on such language-specific phonotactic knowledge. This knowledge is used even in perceiving pseudowords (Aaltonen et al. 2008) or single-vowel sequences (this study). We suggest that knowledge about harmonic sequences in words also affects the perception of the same sequences elsewhere. In this respect, it does not matter whether participants treated the vowel sequences as belonging to one word or not. The fact that disharmonic sequences can occur across word boundaries in Turkish does not preclude the possibility that early perceptual responses treat these sequences as similarly disharmonic as within word boundaries; indeed the disharmony itself may be a pre-lexical indicator relevant for word-segmentation (Kabak, Maniwa, and Kazanina 2010). For a grammatical decision regarding harmony, on the other hand, the word level is indispensable – but one would need another (later) ERP component to assess the processing on this level. The experiment of this study can be a promising starting point towards this future direction.

5. Conclusion

In this article, we have shown that the principle of Turkish vowel harmony and co-occurrence restrictions on vowel sequences are processed pre-attentively, independently of acoustic distances between the vowel stimuli and independently of lexical word representation. We therefore provided neurobiological support for the view that phonotactic knowledge is represented as part of phonological grammar, separate to phoneme representations (Kenstowicz 1994). This knowledge appears to be language-specific and can be theoretically modeled by underspecification theory (Lahiri and Reetz 2002; Kabak 2007) or by ranked constraint interactions (Prince and Smolensky 2004), while purely acoustic or frequency-based approaches cannot satisfyingly account for the neurophysiological data of our experiment.

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