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Locality and harmony: Perspectives from artificial grammar learning

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Abstract

Harmony is one of the most researched phenomena in phonological theory, mainly due to its iterative, nonlocal nature. In this review, I summarize several of the key issues in harmony that can be addressed using an artificial grammar learning approach, including differences between consonant and vowel harmony, transparent and opaque neutral vowels, computational complexity of attested and unattested harmony patterns, and morphological and phonetic influences on harmony. The review demonstrates how the artificial grammar learning paradigm can offer unique insights into the representation of vowel harmony and provides suggestions for ways in which aspects of harmony can be manipulated to offer further insights into the still unanswered questions on harmony and phonological representations.

1 | INTRODUCTION

Harmony, the conditioned agreement of segmental features within a given lexical or prosodic domain, is likely one of the most studied phenomena in phonology. Harmony is important to phonologists for several reasons. First, harmony, particularly vowel harmony, is a pattern that is robust in a variety of languages, across a wide range of language families, including but not limited to Turkish (Turkic; Clements & Sezer, 1982), Finnish (Finno-Ugric; Goldsmith, 1985), Hungarian (Finno-Ugric; Booij, 1984), Pasiego Montañes (Indo-European, Romance; McCarthy, 1984), Turkana (Nilotic; Bakovic, 2001), and Yoruba (Bantu; Archangeli & Pulleyblank, 1989). Second, studying harmony allows researchers to explore a variety of important issues in phonological theory, including the representation of features, representational differences between consonants and vowels, segmental interaction at a distance, and the status of phonetic grounding of phonological patterns. The present review explores issues in vowel harmony and locality from an experimental perspective, primarily focusing on artificial grammar learning studies. This review explores the major questions that arise in the study of vowel harmony that can be addressed using the artificial grammar learning paradigm. For more information about specific theories of vowel harmony and artificial grammar learning in phonology, there are several quality reviews with these specific focuses (e.g., Gafos & Dye, 2011; Rose & Walker, 2011; Moreton & Pater, 2012; Walker, 2012).

2 | WHY STUDY ARTIFICIAL LANGUAGE LEARNING?

In order to gain an understanding of vowel harmony that is both theoretically and cognitively robust, it is necessary to address the issues from a variety of perspectives, including careful fieldwork, broad typological studies, formal theoretical models, computational models, and experimental approaches. Formal analyses and typological surveys are necessary to distinguish between common vowel harmony patterns and unattested patterns but often leave unanswered questions, such as whether unattested languages are the result of computational complexity, language change, or an accidental gap (Moreton, 2008). Artificial grammar learning experiments offer an approach to test the hypotheses that develop as a result of typological study and formal linguistic analysis, in addition to offering insights into learnability and cognition. An abundant set of factors that cannot be controlled in a natural setting (e.g., the lexicon, vowel inventory, morphology, and frequency) can easily be controlled in an artificial grammar learning setting, allowing the researcher to create minimally different languages in order to test a variety of hypotheses about linguistic structure. Second, because it is impossible to test the learnability of theoretically impossible languages in a natural setting, artificial grammar learning paradigms offer a means to address a variety of issues of learnability. For example, two patterns may be learnable, but one pattern may take less time to learn than the other, demonstrating the naturalness of one pattern over the other (Schane et al., 1974). The artificial grammar learning paradigm is particularly well suited to the study of harmony because harmony is relatively easy to learn in a single training session. There have been several experiments showing that adult, native speakers of a language without vowel harmony (e.g., English and German) can acquire a vowel harmony pattern with 10–20 min of training (Pycha et al., 2003; Finley & Badecker, 2008; Moreton, 2008; Finley & Badecker, 2009a; Baer-Henney et al., 2014).

The linking hypothesis in an artificial grammar learning experiment is that if a linguistic difference manifests as a learning difference, then that linguistic difference must be represented differently in the grammar of the language learner or user. Learnability can therefore be used to infer representational factors in phonological processes. One way to do this is through testing learners' generalization to novel items or novel structures. If a learner generalizes the vowel harmony pattern that they learned to a novel item, then we can assume that the learner's representation of the vowel harmony pattern includes the representation that makes this novel item different. Generalization to novel items typically makes use of the poverty of the stimulus paradigm (Wilson, 2006) in which participants are exposed to a subset of the relevant stimuli and then tested on their generalization to novel items. For example, Finley and Badecker (2009) trained participants on a vowel harmony language that included four vowels from a six-vowel inventory. At test, participants were exposed to all six vowels of the inventory, and the generalization to the two novel segments was used to assess whether participants learned the pattern in terms of individual segments (generalization not expected) or in terms of distinctive features (generalization expected). Participants generalized to the novel segments only when the distinctive featural representation of the vowel harmony pattern supported such generalization, suggesting that learners use distinctive features to represent the novel vowel harmony pattern.

One of the major concerns with using artificial grammar learning as a proxy for naturalistic learning is that the cognitive mechanisms involved in artificial grammar learning could be significantly different from natural languages. Although the question of whether artificial grammars are sufficiently similar to natural languages has yet to be determined, current neurological evidence suggests that artificial languages learned in a laboratory evoke the same neurological components for grammaticality as natural languages (Friederici et al., 2002; Morgan-Short et al., 2010; Morgan-Short et al., 2012; Sanders et al., 2015), suggesting that artificial languages may tap into the same representations of natural languages. Therefore, artificial grammar learning of phonology (and harmony specifically) is an important way to gain insights into the constraints that govern phonological processes.

The remainder of this review will focus on five major issues in the study of harmony that have been addressed using artificial grammar learning and show promise for future research. Section 3 compares consonant harmony with vowel harmony. Section 4 explores neutral vowels in vowel harmony (transparent vs. opaque vowels). Section 5 discusses computational characteristics of vowel harmony, including the concept of 'myopia'. Section 6 explores morphological control in vowel harmony, including the locality of domains for harmony. Section 7 explores phonetic influences on vowel harmony and the notion of Strict Locality. Section 8 concludes.

3 | CONSONANTS AND VOWELS IN HARMONY

Rose and Walker (2011) define 'harmony system' as "a term which encompasses consonant harmony, vowel harmony, and vowel-consonant harmony" (p. 240). Harmony can either apply globally to all segments in the harmonic domain, as in Kalenjin, where the presence of the dominant [+ATR] vowel causes all vowels to become [+ATR] (e.g., /kɪ + a + ʊn + kej/ [kiæungej] "I washed myself"; Lodge, 1995) or can apply locally between two segments but no more. For example, in Kashaya, complete (vowel copy) harmony occurs between two adjacent vowels (e.g., [m**i**h**i**'la] "west"; [w**a**ʔ**a**li] "cane") but not beyond (Rose & Walker, 2011). For the purposes of this paper, I will focus primarily on vowel and consonant harmony that apply at a global level.

There are several properties that differentiate vowel and consonant harmony that go beyond whether they apply to vowels or consonants. Vowel harmony patterns often involve consonants, either as participants in the process or as blockers, while consonant harmony rarely involves vowels at a perceptible level. For example, consonants can participate in vowel harmony in Turkish (e.g., /k/ and /l/ have front and back variants that appear in front vowel and back vowel words, respectively (Clements & Sezer, 1982), but vowels typically do not participate in consonant harmony (e.g., sibilant harmony cannot apply to vowels because vowels are not contrastive in this way). This difference is largely due to feature or inventory incompatibility. For example, liquid harmony creates a contrast between /l/ and /r/, and therefore cannot apply to vowels. However, nasal harmony creates contrasts between nasal and non-nasal segments, which can apply to both consonants and vowels (e.g., nasal harmony in Terena [**õn**dopiko] "chopped", 1st sg. subject; Cole & Kisseberth, 1995a). Consonant harmony tends to apply to minor place features (e.g., anterior), while vowel harmony tends to apply to major place features (e.g., back). This may explain why vowel harmony typically applies to the majority of vowels in the language, but consonant harmony typically applies to a much smaller subset of consonants in the language (Jurgec, 2011), as all segments contain a value for major features, but not all segments contain values for minor features.

Phonetic studies have suggested that many vowel harmony systems result from a historical shift (phonologization) of vowel-to-vowel coarticulation, when two or more speech sounds are produced (articulated) at the same time (Boyce, 1990; Ohala, 1994; Beddor & Yavuz, 1995; Majors, 1998; Beddor et al., 2002). Consonant harmony, on the other hand, results from constraints on speech planning (Dell et al., 1997; Hansson, 2001; Hansson, 2007). These differences in phonetic grounding between consonant and vowel harmony may explain differences in tolerances for locality violations.

If vowel harmony is grounded in coarticulation, which is a necessarily local process (overlapping of gestures), it predicts that vowel harmony should be less tolerant of locality violations than patterns that are derived from speech planning, which need not to be local. This prediction holds typologically; consonant harmony tends to show more cases where the trigger and the target are nonlocal, sometimes multiple syllables away, whereas vowel harmony shows much fewer cases of nonlocality. Although experiments have not directly compared vowel harmony to consonant harmony, artificial grammar learning experiments have shown that English speaking participants could easily learn a sibilant harmony pattern that applied across more than two syllables (e.g., [**ʃ**akedo**ʃ**u] vs. *[**ʃ**akedo**s**u]; Finley, 2012a), but struggled to learn a vowel harmony pattern that applied across a single neutral transparent vowel in a back or round harmony pattern (e.g., [p**o**dɛg**o**] vs. *[p**o**dɛg**e**]; Finley, 2015a). These results suggest that learners show a stronger bias against nonlocal patterns in vowel harmony than in consonant harmony.

One reason that it is difficult to directly compare distance-based effects between consonant and vowel harmony is there are significant representational differences between consonants and vowels. Because most every syllable contains a vowel, but not every syllable contains a sibilant consonant (or the relevant consonant for consonant harmony), it is more likely that the presence of multiple sibilants in a single word may span more than two syllables. In addition, the differences in the featural representation of vowels and consonants may support more long-distance patterns for consonant harmony. Because consonants are typically analyzed using a larger set of distinctive features than vowels (Chomsky & Halle, 1968),[1] it may be easier to separate consonantal features into separate tiers, which may allow for more long-distance processes to occur (Heinz, 2010; McMullin, 2016).

Although consonant harmony may be more tolerant of long-distance agreement, learners nevertheless appear to be biased towards local representations in consonant harmony (Finley, 2011; McMullin & Hansson, 2014; McMullin, 2016). Finley (2011) showed that participants who were exposed to a sibilant harmony pattern that applied across an intervening syllable (e.g., /ʃataʃu/) generalized to the harmony pattern that applied to adjacent syllables (e.g., /taʃaʃu/). However, participants exposed to the more local pattern (e.g., /taʃaʃu/) did not generalize to a pattern that crossed an intervening syllable, suggesting a bias towards locality (Finley, 2012a; McMullin & Hansson, 2014; McMullin, 2016).

Consonant and vowel harmony also show differences in constraints on directionality, which may stem from differences in phonetic grounding. Consonant harmony shows a relatively strong bias towards right-to-left directionality, which has been explained in terms of speech planning, as the speaker harmonizes in anticipation of an upcoming segment (Hansson, 2001). Although Hyman (2002) has suggested that vowel-consonant-vowel (VCV) coarticulation may produce a right-to-left bias for vowel harmony, this bias is often masked by morphological control (Hyman, 2002). In stem-controlled vowel harmony, where feature of the stem vowel determines the features of the affix vowels, directionality is determined by the affix: languages with prefixes are more likely to show right-to-left directionality, while languages with suffixes are more likely to show left-to-right vowel harmony (Bakovic, 2000).

When participants were exposed to a vowel harmony pattern that was unambiguously directional (e.g., not controlled by the feature value of the stem), participants exposed to a left-to-right pattern in the learning phase were able to generalize the harmony to a right-to-left pattern, but participants exposed to right-to-left pattern failed to extend the harmony to a left-to-right pattern (Finley & Badecker, 2009b). Although the directionality bias in consonant harmony has not been explored in an artificial grammar learning paradigm, both directions appear to be learnable: McMullin and Hansson (2014) showed learning of right-to-left sibilant harmony, while Finley (2011) showed learning of left-to-right sibilant harmony.

In consonant harmony, "interacting segments share a high degree of similarity" (Rose & Walker, 2004, p. 484). Rose and Walker (2004) cite several consonant harmony patterns in which the interacting consonants are highly similar, including Chaha, where oral stops participate in laryngeal harmony based on their similarity to each other (e.g., voicing, place). Although similarity effects are commonplace in consonant harmony, similarity effects in vowel harmony are typically relegated to a specific, less common type of vowel harmony, referred to as parasitic harmony. In parasitic harmony, agreement for feature A only occurs when the vowels already agree in feature B (e.g., in the Yalumne dialect of Yokuts, also referred to as Yawelmani round harmony only applies when the two vowels agree in height (Cole & Trigo, 1989; Wayment, 2009; Jurgec, 2011). This parallel between similarity in consonant harmony and parasitic harmony has led some scholars to suggest that consonant and vowel harmony could be analyzed using a similar theoretical framework such as Agreement by Correspondence (Rose & Walker, 2004), where agreement is required only when segments are in correspondence, which requires some degree of similarity (Sasa, 2009; Rhodes, 2012; Bowman & Lokshin, 2014; Walker, 2014). An important point, however, is that parasitic vowel harmony never seems to involve transparent segments, but parasitic consonant harmony (as in Kalasha, Arsenault & Kochetov, 2011)[2] can skip intervening consonants. Although the issue of parasitic harmony and similarity has not yet been addressed in artificial grammar learning studies, future work could manipulate similarity in both consonantal and vowel features to better determine the role of similarity in learning.

4 | TRANSPARENT VERSUS OPAQUE VOWELS

One of the biggest theoretical issues surrounding vowel harmony is the representation of neutral vowels—vowels that fail to either undergo or trigger vowel harmony. There are two main types of neutral vowels in vowel harmony: opaque and transparent. Opaque vowels block agreement between vowels and may create a new harmony domain. For example, in Turkish, non-high vowels are opaque to round harmony (e.g., [syt-e-mi], *[syt-ø-my] "is it milk"-DAT; Gafos & Dye, 2011). A transparent neutral vowel is a vowel that neither spreads the harmonic feature nor takes on the harmonic feature as a result of spreading. In Hungarian (a language with front or back harmony), the suffix vowel agrees with the back feature of the stem vowels (e.g., [haja-nak], "ship"-DAT-SING). However, if the final vowel of the stem is the front transparent neutral vowel /i/, and the stem contains a back vowel, then the suffix will be back, in agreement with the back vowel in the stem (e.g., [radir-nak] "erase"'-DAT; Booij, 1984). Not only is the transparent vowel completely inert, the spreading process appears to apply right through the vowel.

Although both transparent and opaque vowels are well attested across several vowel harmony languages, transparent vowels pose a challenge for any analysis of harmony that requires agreement between adjacent segments. Typically, transparent vowels are accounted for with additional rules, constraints, or representations, while opaque vowels are accounted for using the default mechanisms (Bakovic & Wilson, 2000). For example, Bakovic and Wilson (2000) account for opaque vowels in optimality theory (OT; Prince & Smolensky, 2004) using a standard AGREE constraint (which requires adjacent vowels to share the same value of the harmonic feature) but require additional targeted constraints to account for transparent vowels. Table 1 shows a hypothetical back or round harmony system in which the low vowel /a/ cannot participate due to a high-ranked inventory constraint (*Round or Low [Kaun, 2004], candidate [c]). For ease of explication, the target vowels are left unspecified in the input representation and therefore do not violate faithfulness constraints.[3] Candidate (a), the opaque candidate, is preferred to candidate (b), the transparent candidate, because

TABLE 1 AGREE constraints prefer opaque to transparent vowels (adapted from Bakovic and Wilson (2000))

/uAI/	*Round & Low	AGREE[Round]
☞ a. uai (opaque)		* (ua)
b. uay (transparent)		*(ua)* (ay)!
c. uɔy (harmonic)	*!	

candidate (a) has only one violation of AGREE, between [u] and [a] while the transparent candidate (b) incurs and additional violation of AGREE, between the vowels [a] and [y]; the opaque candidate harmonically bounds the transparent candidate.

The relative ease of accounting for opaque vowels compared to transparent vowels poses a question of whether this difference translates to a learnability difference. Finley (2015a) trained adult, English speaking participants on a novel back or round harmony pattern with a neutral vowel [ɛ]. The languages were minimally different except that in one language, the neutral vowel was opaque, and in the other language, the neutral vowel was transparent. Participants in the opaque condition successfully learned the behavior of the opaque vowel, while participants in the transparent condition learned the general harmony pattern but failed to learn the behavior of the transparent vowel. The transparent vowel could only be learned when the number of crucial trials containing the transparent vowel was significantly increased. These results suggest that the complexity of representations required to account for neutral vowels may be encoded in learning about transparent vowels.

Transparent vowels demonstrate vowel-to-vowel agreement across an intervening syllable. However, agreement across transparent vowels does not appear to be unbounded. The more transparent vowels intervene between the two agreeing vowels, the less likely vowel harmony is to apply. This phenomenon is referred to as distance-based decay (Kimper, 2011a; Zymet, 2015) and has been shown to be robust in Finnish (Krämer, 2003; Jurgec, 2011) and Hungarian (Hayes & Londe, 2006). Distance-based decay is often not categorical, leading to the question of whether distance-based decay is extragrammatical or if it is a part of the learned representation of the vowel harmony pattern. Although Hayes and Londe (2006) provide evidence for the psychological reality of stochastic differences in neutral vowels, artificial grammar learning experiments could help to further understand the extent to which learners are biased towards certain stochastic patterns like distance-based decay by manipulating the number and type of neutral vowels.

5 | VOWEL HARMONY AND MYOPIA

Although harmony is often described as an unbounded process, applying iteratively to an unlimited set of syllables, harmony appears to be sensitive only to the local surrounding context, rather than the global context (Walker, 2010). This narrow-focused sensitivity is referred to as “myopia” (Walker, 2010; Kimper, 2012; Heinz & Lai, 2013). An intuitive way to characterize myopia makes use of Nevins’ (2010) search procedure, whereby a harmony target searches for its nearest possible donor (or trigger). Once a suitable donor is found, the search ends. Harmony is myopic because the search cannot “see” past the first suitable donor. Because no known attested vowel harmony language violates myopia in the absence of robust morphological control, it is important that all proper theories of vowel harmony should predict myopia. However, OT readily predicts unattested violations of the myopia principle (Wilson, 2005).

One such unattested pattern is “majority rules”. Majority rules is a pathological pattern in which the direction of agreement (left or right) is determined by the majority feature within the word. This

TABLE 2 AGREE constraints predict majority rules

/++−/	AGREE [F]	ID [F]
☞ a. +++		*
b. − − −		**!
/+− −/		
☞ a. − − −		*
b. + + +		**!

pathology demonstrates a violation of myopia because in majority rules, agreement is based on the total number of vowels in the word, a global property, rather than local agreement between adjacent vowels. In Table 2, when AGREE [F] outranks, ID [F], the direction of spreading is based on the number of ID violations, rather than the specific feature value, or a specified direction. For both inputs, candidate (a) wins because it satisfies AGREE with the fewest ID violations.

Although majority rules patterns are easy to produce in OT, they are unattested in natural language. To test whether learners show a bias against this type of pathology, Finley and Badecker (2009) tested whether learners were biased for directional patterns over majority rules patterns by training participants on a pattern that was ambiguous between a left-to-right pattern and a majority rules pattern (e.g., /++−/→[+++]). At test, participants were given the option to reverse the direction (e.g., /−++/→[+++]) to preserve majority rules, violating myopia, or keep the direction (e.g., /−++/ →[− − −]). When the direction was reversed, participants chose the minority pattern to preserve the direction of agreement, suggesting that learners are biased towards directionality over majority rules. These results support the hypothesis that pathological patterns like majority rules are outside of the set of phonological patterns that learners are attuned to find when learning a novel phonological pattern.

Formal language theory may help further our understanding of harmony and locality. As Heinz (2010) notes, “a debate about the nature of locality in phonology is also a debate about computational complexity in phonology” (Heinz, 2010; 626). Formal language theory does not rely on specific theories of features or tiers and can therefore be applied to a variety of formal frameworks (Rogers et al., 2013). Although this paper aims to provide explanations of formal properties in plain, simplified language, the curious reader is advised to refer to one of many papers on the topic of formal language theory and phonology (Heinz et al., 2011; Heinz, 2011; Rogers et al., 2013; Chandlee, 2014; Jardine, 2016; McMullin, 2016).

Phonological patterns can be expressed computationally as regular expressions (Kaplan & Kay, 1994).[4] A regular expression is in simple terms, a grammar that evaluates the goodness (or grammaticality) of sets of strings of an input form being mapped to some output form. Sound Pattern of English–style (SPE) rules (Chomsky & Halle, 1968) are a good example of regular expressions because they involve a simple rewrite from input to output (e.g., A ➔ B / C_D). Although all potential SPE rules can be generated through regular expressions (Kaplan & Kay, 1994), the class of regular expressions alone is too large to predict, which rules are possible and, which are unattested. Without any restrictions, grammars based on the entire set of regular expressions will overgenerate (e.g., generate an arbitrary rule requiring three /p/ sounds in every word; Heinz, 2011). Because formal language theory provides a means for defining computational complexity in sets of languages, formal language theory can supply a platform to restrict regular expressions in terms of computational complexity and typological well-formedness. One such restriction is that phonological patterns fall into subclasses of regular expressions (e.g., phonological patterns are Subregular), and that these sets can be classified hierarchically in terms of computational complexity (Heinz & Lai, 2013; Rogers et al., 2013).

According to the Subregular Hypothesis (Heinz, 2010; Lai, 2015; Hwangbo, 2016), the more complex the regular language, the more difficult it will be to learn. Several artificial grammar learning experiments have manipulated computational complexity, showing that more computationally complex patterns tend to be more difficult to learn (Lai, 2015; Hwangbo, 2016; McMullin, 2016). For example, Lai (2015) showed that English-speaking participants were able to learn a standard sibilant harmony pattern but not a nonlocal sibilant harmony pattern in which the first consonant of the word must agree with the last consonant of a word, regardless of the intervening consonants (first-last harmony). For example, [**ʃ**atasa**s**] violates first-last sibilant harmony even though there is a potential blocker (/t/), and the final two sibilant consonants agree. First-last harmony patterns are computationally more complex, as this set of languages does not fall into the class of attested subregular languages (Mailhot & Reiss, 2007). Participants who were trained on a first-last harmony pattern showed responses consistent with a standard sibilant harmony pattern, even when training only contained items consistent with a first-last pattern, suggesting that the learners in Lai's (2015) experiment were biased towards a standard sibilant harmony pattern and against a first-last harmony pattern.

Further support for the Subregular Hypothesis comes from an artificial grammar learning experiment that compared the learnability of two different backness vowel harmony patterns: Rightmost and At Least One. Rightmost harmony is essentially a stem-controlled left-to-right harmony in which the suffix vowels agree with the feature carried by rightmost stem vowel (Hwangbo, 2016). At Least One is a vowel harmony pattern in which the suffix vowel is determined by a dominant feature in the stem. The suffix vowel takes on the feature of the dominant vowel if there is at least one dominant nonneutral vowel in the stem. This type of pattern is a type of dominant-recessive harmony (Bakovic, 2000). Although both types of languages are possible in natural language, according to formal language theory, Rightmost languages fall into a relatively complex class of regular languages (Non-Counting), while At Least One languages fall into a relatively simple class of languages (Locally Testable). At Least One languages are computationally less complex than Rightmost languages in part because it is possible to determine the harmonic feature of the word in an At Least One Language without reference to location in the word; choose the dominant feature if found, otherwise choose the nondominant feature. Rightmost languages, on the other hand, require the location of the final stem vowel to determine the feature of the suffix: the third vowel in a three-syllable stem and the fourth vowel in a four-syllable stem. Hwangbo (2016) trained participants on a vowel harmony pattern that either adhered to the Rightmost or the At Least One patterns. In the crucial test items, only participants in the At Least One condition showed a significant difference from the control condition, suggesting that the At Least One pattern was easier to learn, supporting computational complexity in learnability.

Another way that formal language theory characterizes differences in attested and unattested phonological patterns is a property of regular expressions known as subsequentiality. A subsequential regular expression is a directional regular expression (defined as either right subsequential or left subsequential) in which the evaluation of grammaticality of a word (or string) can proceed from right to left (or left to right) without reference to previously analyzed strings (going backwards), or reference to the nonlocal context. For example, in a majority rules pattern, the input–output mapping /+ − − −/: [+ + + +] is ungrammatical because the minority feature /+/ "spreads". An iterative, left-to-right evaluation would not be able to correctly reject the ungrammatical mapping without going backwards through the string (Gainor et al., 2012; Heinz & Lai, 2013), predicting the impossibility of majority rules when non-subsequential languages are ruled out. All attested vowel harmony patterns[5] can be accounted for using subsequential evaluation, but unattested patterns, specifically ones that violate the myopia principle, cannot be characterized as subsequential (Gainor et al., 2012; Heinz & Lai, 2013).

Formal language theory has the potential to offer great insight into the cognitive mechanisms involved in learning and representing harmony (Rogers & Pullum, 2011; Jager & Rogers, 2012). McMullin (2016) and Heinz (2010) suggest that different classes of regular expressions may trigger different learning strategies. If learners are biased towards the simplest regular expression or learning strategy, it may explain why some phonological patterns are cross-linguistically more likely to occur, and why participants in artificial grammar learning experiments appear to ignore their exposure stimuli in favor of a simpler pattern.

6 | MORPHOLOGY VERSUS PHONOLOGY

Computational analyses of the complexity of phonological patterns typically do not take into account syntactic or morphological information. As Heniz and Idsardi (2013) note, the computational complexity of syntactic and morphological patterns may be higher, suggesting that with semantic or morphological support, it may be possible to learn a more computationally complex pattern. For example, some metaphony patterns target stressed vowels and can skip as many unstressed vowels as necessary until the stressed target is hit (e.g., Lena, (Hualde, 1989; Veneto; Walker, 2010), appearing to violate locality and myopia. However, these patterns tend to apply only in specific morphological contexts (Dillon, 2003).

Finley (2009) refers to this type of morphologically controlled harmony as morphemic harmony. For example, the Kanembu incompletive is marked by [−ATR] on all vowels in the word, while completive forms are marked by [+ATR] on all vowels in the word (Akinlabi, 1996). To test whether the morphemic vowel harmony is more tolerant of locality violations, Finley (2012c) trained participants on a first-last consonant harmony pattern that was either morphemic (marking a distinction between singular and plural) or phonological (not marking any morphological category). Participants were only able to learn the first-last harmony pattern in the morphemic condition, suggesting that a morphological marker may make it easier to learn a harmony pattern with a locality violation.

Because vowel harmony often applies to affixes (e.g., in Turkish and Hungarian), exceptions to vowel harmony are often observed in terms of morphological control. For example, in Turkish, the suffix [−gen] does not alternate, allowing for both harmonic and disharmonic forms (e.g., [sekiz-gen-ler] "octocgonals", [tʃok-gen-ler] "polygonals" Clements & Sezer, 1982). Finley (2015b) trained English-speaking adults on a novel vowel harmony language where one suffix alternated depending on the back or round features of the stem vowels (i.e., [−me]/[−mo]), and another suffix did not alternate (i.e., was always [−go-]). Participants learned the harmonizing behavior of the alternating suffix and accepted disharmony in the case of the non-alternating suffix. However, participants were more likely to select the correct response to items containing the non-alternating suffix when that suffix appeared in a harmonic context (i.e., a round vowel stem). These results suggest that learners may be biased for harmony to apply, despite exposure to disharmony.

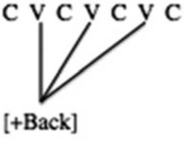
Vowel harmony can apply iteratively across several morphological domains, but there is no language (to my knowledge) in which vowel dissimilation applies in the same iterative fashion, where all adjacent vowels must be dissimilar. Although harmony and disharmony are both learnable in an artificial grammar learning setting (Pycha et al., 2003), it is unclear whether learners would show the same ease of learning for an iterative disharmony pattern compared to an iterative harmony pattern.

The morphological control of vowel harmony is often represented in terms of domains. Several accounts of vowel harmony in OT rely heavily on the concept of a domain. For example, Span Theory (O'Keefe, 2007), Optimal Domains Theory (Cole & Kisseberth, 1995a; Cole & Kisseberth, 1995b; Cole & Kisseberth, 1995c), and Headed Feature Domains Theory (Smolensky, 2006) all rely on the notion that harmony is induced by agreement of vowel features within a particular domain. That domain could be as small as a single vowel or syllable, or it could be as large as an entire sentence. The use of domains in many theories poses the question about the optimal restrictions on domain-based agreement. Kimper (2011b) cites the need for domain-based constraints in order to demonstrate differences in domain of application. Some harmony patterns appear to apply iteratively across morpheme and word boundaries, while other patterns apply only within the word or set of morphemes. Although there is an intuition that within-word domains should take priority over a domain outside the word, Kimper (2011b) notes that there is at least one case where harmony applies across a word boundary but not within a word. An artificial grammar learning paradigm could help tease apart some of the questions about domains. Meyers and Padgett (2014) showed that learners show a preference for word-based generalization in an artificial grammar learning task, and we can conjecture that the same principle of a bias towards the word domain over larger domains may also hold in vowel harmony.

7 | PHONETICS VERSUS PHONOLOGY

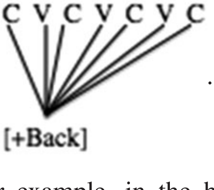
The parallels between phonetically grounded vowel harmony and VCV coarticulation (Ohala, 1994; Beddor & Yavuz, 1995; Hyman, 2002) raise the importance of phonetic representations in vowel harmony. The influence of coarticulation in the representation of vowel harmony patterns has played an important role in the debate about the locality of vowel harmony. Strict Locality is the hypothesis that the gestures that produce vowel harmony necessarily overlap between the vowels and consonants in the sequence (NiChiosain & Padgett, 2001). Most theories of vowel harmony assume some kind of relative harmony, (as shown in Relativized Locality), where vowel harmony applies only to vowels, skipping consonants. This can be achieved by representing vowels and consonants on separate tiers, or by allowing the formulation of rules and constraints to target consonants and vowels separately.

(3) Relativized Locality: (NiChiosain & Padgett, 2001)



Strict Locality requires that all phonological processes apply iteratively across adjacent segments, meaning that agreement or spreading passes through intervening consonants and vowels, but not necessarily in a way that affects the phonological representation of these consonants and vowels.

(4) Strict Locality: (NiChiosain & Padgett, 2001)



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For example, in the hypothetical sequence /eku/ [eky], where the feature [−Back] spreads from the initial vowel to the final vowel, the initial vowel /e/ spreads [−Back] through the intervening consonant /k/, where the final vowel "picks up" the [−Back] gesture. The question then is what happens to the representation of /k/, a dorsal consonant with an added [−Back] gesture. According to NiChiosain and Padgett (2001), all vowels and consonants undergo spreading, but language specific optimization on vowel and consonant inventories determines the surface form of these consonants. In this hypothetical example, when /k/ undergoes spreading, it becomes $[k]_{[-\text{back}]}$ and will surface as either a palatal or a plain [k], depending on inventory constraints derived from dispersion theory (Lindblom, 1986).

Strict Locality predicts that there will be languages in which harmony only applies across two adjacent vowels (hiatus) but not across consonants. In Turkish, back or round harmony applies across consonants, but a type of height harmony may apply in hiatus; when two vowels are adjacent, the second vowel lowers to become identical to the first vowel (Kabak, 2007). Other support for Strict Locality comes from articulatory phonology. Harmony can be derived from natural segmental overlap (Browman & Goldstein, 1992) in which the harmonic feature on the vowel overlaps with the entire consonantal gesture, so that the nearest vowel can "take over" the gesture for the harmonic feature. If gestural overlap is not possible, then that consonant (or vowel) may serve as a harmony blocker (Gafos, 2002). For example, in Buchan Scots, harmony is blocked by consonants that cannot take a secondary articulation (Paster, 2004), suggesting that these consonants block harmony due to a failure in gestural overlap. In addition, as the distance between the source and target for harmony increases, the ability of the speaker to maintain a given gesture decreases, providing a potential account of distance-based decay effects, defined above.

Data from articulatory phonetics (Benus & Gafos, 2007) showed that Hungarian speakers produce transparent vowels differently depending on the context. Stems that contain a transparent vowel that trigger back vowel suffixes are pronounced with a gesture that is further back, while stems that contain a transparent vowel that trigger front vowel suffixes are pronounced with a gesture that is further front even when there is no suffix. This suggests that the representation of transparent neutral vowels carries some phonetic code of the following vowel, as predicted by Strict Locality. However, it is not clear whether these differences in production may be detectable in the acoustics in a way that could affect the learning process. An artificial grammar learning paradigm that specifically controlled for acoustics could help to tease these hypotheses apart.

Articulatory factors may also play a role in determining whether one vowel is more likely to be a transparent vowel than another. In back vowel harmony, the probability that a vowel will be transparent increases with vowel height; high vowels are more likely to be transparent than non-high vowels. The relative likelihood of transparency could be explained in terms of articulatory phonetics; vowels whose gestures are more easy to overlap with other gestures for a long period of time may be more likely to be transparent (Smith, 2016). This is consistent with both Rebrus and Torkenczy's (2015) approach to transparency that requires transparent vowels in back harmony to be intermediate between a front and back vowel, and the gestural harmony model, which is based on an updated version of articulatory phonology (Smith, 2016).

According to the gestural harmony model, vowel harmony occurs when gestures overlap. However, gestures that are either incompatible or antagonistic do not overlap. When gestures are incompatible, it is possible to produce the two gestures at the same time, but the result is marked (e.g., a low, round vowel). When two gestures are antagonistic, the two gestures fail to overlap, and harmony is blocked (e.g., an opaque vowel). Gestures are antagonistic when the gesture of one vowel directly opposes the gesture of another vowel, and the result is a weighted average of the two gestures. According to the gestural harmony model, "transparency is the result of the concurrent activation of two antagonistic gestures. Blocking, on the other hand, is the result of a ban on the concurrent activation of two incompatible gestures" (Smith, 2016, p. 5). Note that incompatible gestures can also be resolved via blocking (the same solution for antagonistic gestures), but antagonistic gestures cannot be resolved as a result of concurrent activation. This results in the prediction that vowels that can be transparent are a subset of the vowels that can be opaque to vowel harmony. Although Smith (2016) claims that this implicational universal holds for round and nasal harmony, it is not clear whether this asymmetry holds for other types of harmony. However, recent artificial grammar learning experiments exploring the learnability of transparent vowels in back vowel harmony suggest that learners are sensitive to the fact that high vowels are better transparent vowels than mid vowels in back vowel harmony (Ozburn & Hansson, 2016).

Differences in the likelihood of a vowel being transparent may also be related to perceptual factors that determine whether a vowel is able to trigger vowel harmony (Kimper, 2011a). If a vowel is able to trigger harmony, then it has the potential to be a transparent vowel, but if a vowel is unable to trigger harmony, then the vowel will not be transparent. Kaun (2004) suggested that perceptually weak round vowels are typologically more likely to trigger round vowel harmony. Kaun (2004) hypothesized that harmony serves as a way to support the perception of perceptually weak vowels. By spreading the rounding feature in a weak position (e.g., front or non-high), it may make it easier for the listener to perceive the rounding feature on the triggering vowel. Support for this hypothesis comes from experiments showing that languages with preferred round vowel harmony triggers are easier to learn than languages with dispreferred triggers (Finley, 2012b; Kimper, 2016). Finley (2012b) trained English-speaking adults on a left-to-right back or round harmony pattern that either had high vowels as triggers (e.g., /budu-gu/, /budu-mo/), which are typologically less likely to trigger round vowel harmony (Kaun, 2004), or mid vowels as triggers (e.g., /bodo-gu/, /bodo-mo/), which are typologically preferred round harmony triggers. Participants were able to learn the harmony pattern with mid vowel harmony triggers but not high vowel harmony triggers, suggesting a bias towards typologically and perceptually preferred harmony triggers.

Perceptual effects may also help to explain cases of transparency that may not be explainable in terms of gestural overlap. Kimper (2011a) showed that English-speaking listeners are better at recognizing a vowel as round if there is another round vowel in the word (i.e., is harmonic), and this was true even when there was a neutral vowel in between the target vowel and the harmonic vowel. This suggests that the perceptual benefits of round vowel harmony (Kaun, 2004; Walker, 2005) may apply even when Strict Locality does not apply. Experimental methods, like those of Kimper (2011a), could help distinguish between Strict Locality and Relativized Locality accounts of vowel harmony. It may also be possible to use artificial grammar learning techniques to test the possibility that fine-grained phonetic effects play a role in learning and are part of the learned representation of vowel harmony patterns.

8 | CONCLUSIONS

This review has covered several topics in harmony that can be addressed using the artificial grammar learning paradigm. Section 2 explored the benefits of artificial grammar learning experiments. Section 3 discussed differences between consonant and vowel harmony, including differences in phonetic grounding, directionality, and locality. Section 4 compared the representational and learning differences between transparent and opaque neutral vowels in vowel harmony. Section 5 addressed the role of myopia in vowel harmony. Despite the fact that harmony is considered a long-distance phenomenon, it still adheres to several constraints on locality. Formal phonology can provide insights into the typological well-formedness of harmony patterns, providing important predictions for learnability, which can be tested in artificial grammar learning experiments. Section 6 addressed issues of morphology in vowel harmony, suggesting that some violations of locality may be governed by morphological control. Section 7 discussed the role of phonetics in vowel harmony, particularly the role of Strict Locality and gestural accounts of harmony.

This paper focused on long-distance vowel and consonant harmony rather than local harmony (e.g., umlaut) or other consonant-vowel harmony patterns. This is largely because there is little or no research on these types of harmony systems using artificial grammar learning experiments. Such experiments would provide important insights into questions of locality and consonant-vowel harmony interactions.

The research discussed in this paper provides a multidisciplinary approach to understanding harmony (typological, computational, theoretical, and experimental). Such an approach makes it possible to have a richer understanding of harmony, one that taps into the cognitive representations of the speaker and learner, providing an important contribution to the cognitive science of language.

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NOTES

[1] Note, however, that the analysis of consonants and vowels depends on the specific theory. Although Chomsky and Halle (1968) list more features for consonants than vowels, other theories, such as Element Theory in Government Phonology (Pöchtrager & Kaye, 2013) in which the basic units (elements) for segments can be shared among consonants and vowels.

[2] Thank you to an anonymous reviewer for pointing this out.

[3] Note that the analysis shows the same issues, regardless of whether the input is fully specified.

[4] Beesley and Karttunen (2003) provide a comprehensive, accessible treatment.

[5] Note that Heinz and Lai (2013) argue that transparent vowels receive a subsequential analysis by incorporating insights from Nevins' (2010) "search" procedure.

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