Explaining Sour Grapes Harmony's Unattestedness with Agent-Based Modeling

Brandon Prickett

1. Introduction

Vowel harmony is a typologically common phonological pattern that restricts which kinds of vowels can appear together in a surface form, often causing all of a word's vowels to agree in their value for one or more features (Rose & Walker, 2011).[1] Harmony patterns are frequently studied in computational phonology (e.g., Hare, 1990; Mailhot, 2013; Gouskova & Gallagher, 2020), with work often focusing on explaining the absence of unattested generalizations (see, e.g., Heinz et al., 2011; Jardine, 2016; Lamont, 2019a). The unattested pattern that this paper focuses on is *Sour Grapes Harmony* (Bakovic, 2000; Wilson, 2006; Finley, 2008; Lin & Myers, 2010).

Attested harmony patterns often involve *blocker segments*, which "block" harmony in the sense that different values of the relevant feature are allowed on either side of the blocker (Rose & Walker, 2011:§3.3.3). For example, if a backness harmony pattern was blocked by [a], the form [tipitaku] would be grammatical, despite the fact that [u] and [i] have different values for the feature [back].[2] Crucially, in a standard pattern like this, all of the vowels to one side of a blocker (e.g. the first two [i]'s in this example) still share the same value for the harmonizing feature.

Sour Grapes is identical to attested harmony patterns when no blocker is present in a word—but when there *is* a blocker, disharmonic sequences can appear either to its left or right, depending on the directionality of the Sour Grapes harmony (Bakovic, 2000; Wilson, 2006). For example, left-to-right Sour Grapes patterns allow disharmonic sequences to the left of a blocker. So, if backness was harmonized in such a pattern, a form like *[tiputu] would be banned, but a form like [tiputaku] would be grammatical, because, in the latter word, the blocker [a] licenses the disharmonic vowels to its left.

Sour Grapes is predicted by a number of constraint-based (Prince & Smolensky, 1993) theories of harmony (Bakovic, 2000; Wilson, 2006), and a number of different explanations for its typological absence have been proposed. These explanations usually take one of two approaches: they either revise the set of constraints used to capture harmony so that Sour Grapes cannot be captured by the phonological grammar (e.g., Wilson, 2006; McCarthy, 2011) or focus on the formal complexity of Sour Grapes and work toward a theory of phonology that categorically prohibits any patterns that are that complex (e.g., Heinz, 2018; Smith & O'Hara, 2019a; Lamont, 2019b). Crucially, both of these approaches seek to categorically limit the grammar so that it lacks the expressive power to ever capture Sour Grapes harmony. However, past experimental work has struggled to find evidence that Sour Grapes *is* categorically unrepresentable (Lin & Myers, 2010; Prickett, 2023).

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[1] Note that vowel harmony can be framed either as a mapping (from a disharmonic underlying form to a harmonic surface form) or as a phonotactic restriction (only allowing harmonic sets of vowels in surface forms). In this paper, I use the latter—for more on the differences between these two ways of conceptualizing phonological patterns, see Prince and Tesar (2004) and Gorman (2013), and for a discussion on this distinction that specifically addresses Sour Grapes, see Lamont (2019b).

[2] For an attested pattern with similar blocking, see Turkish, which has a roundness harmony pattern blocked by any non-high vowels (see Gafos & Dye, 2011 for a description of this and other blocking patterns).

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In this paper, I present results from agent-based simulations using a maximum entropy phonotactic model (Hayes & Wilson, 2008; Moreton et al., 2017) with a set of constraints that has been shown to capture human behavior in an artificial language learning experiment (Prickett, 2023). These constraints allow the model to represent *both* Sour Grapes and more standard, attested harmony patterns. By using agent-based simulations, I'm able to combine the model's theory of representation with a theory of how learnability might shape typology across multiple generations (Kirby & Hurford, 2002) to test whether an explanation for Sour Grape's absence can be explained.

The paper proceeds as follows: §2 discusses past theoretical and experimental work on Sour Grapes harmony, §3 presents agent-based simulations meant to model the diachronic stability of Sour Grapes, and §4 concludes.

2. Background

2.1. Theoretical work on Sour Grapes

Several optimality theoretic (Prince & Smolensky, 1993) approaches to harmony, such as AGREE constraints (Bakovic, 2000; Wilson, 2006), predict Sour Grapes in systems that include a blocker segment. This is because constraints like AGREE penalize words with blocker segments, regardless of whether vowels to one side of the blocker are harmonized. For example, the words [tiputaku] and [tipitaku] would both incur a violation of AGREE(back)—the former because of the [i...u] sequence in the first two syllables and the latter because of the [i...a] sequence in the second and third syllables. This means that both forms would be expected in a language that has a constraint enforcing [a]'s role as a blocker (such as *[-high, -back]) ranked or weighted more highly than AGREE, and AGREE ranked or weighted more highly than a constraint enforcing faithfulness to underlying values of [back]. However, Sour Grapes is an unattested phonological pattern, inspiring a range explanations for this absence.

Wilson (2006) proposed that the reason for Sour Grapes' unattestedness is that attested harmony patterns are *myopic* and Sour Grapes fails to meet this criterion. That is, to determine whether a word is grammatical according to attested patterns, one only needs to look at each of its vowels two at a time, with no need to check pairs of non-adjacent vowels[3] or to look at more than two vowels at once. Since blockers in Sour Grapes license strings of disharmonic vowels of arbitrary length, one needs to look at a potentially infinite window of vowels to determine whether a word is grammatical, to ensure a blocker isn't at its end. Wilson (2006) suggested that a variant of optimality theory (Prince & Smolensky, 1993) that uses *targeted constraints* (Wilson, 2001), would solve this issue by only predicting myopic harmony patterns. Targeted constraints do this by spreading the harmonizing feature in a word one vowel at a time and never looking ahead to non-adjacent vowels.

McCarthy (2011) proposed SHARE constraints, paired with *Harmonic Serialism* (McCarthy, 2000) as a similar method for avoiding non-myopic harmony patterns, including Sour Grapes. SHARE constraints penalize any adjacent pair of segments that fail to share the same feature value. For example, the form [tiputaku] would incur three violations of the constraint SHARE(back), because no pair of adjacent vowels has the same value for the feature [back] (assuming [a] is a central vowel). But the form [tipitaku] would only incur two violations of the SHARE constraint, since the [i...i] pair in the word's first two syllables does have the same value for the crucial feature. This, combined with Harmonic Serialism's limited GEN and a constraint motivating [a]'s status as a blocker, allows attested blocking patterns while categorically preventing Sour Grapes from being represented in the grammar.

However, these approaches have been critiqued, since a number of non-myopic phonological patterns *do* seem to exist (Walker, 2010; Jardine, 2016; McCollum & Essegbey, 2018; Stanton, 2018). Since targeted constraints and SHARE constraints both categorically restrict a grammar so that it can only represent myopic harmony, these patterns are evidence that myopia is not the crucial factor causing Sour Grapes to be unattested.

Another approach for explaining Sour Grapes' absence is *Formal language Theory* (FLT; Chomsky, 1956). FLT is a way of describing how complex a pattern is in terms of the computational machinery needed to represent it. The framework was originally designed to demonstrate that natural language

[3] Throughout this paper, when using the terms "adjacent" as shorthand for "adjacent on the vowel tier of a word." That is, "adjacent, when ignoring any consonants."

syntax was more complex than the set of *regular* patterns (i.e., those that could be represented using finite state machines). However, Johnson (1972) showed that all known phonological mappings *could* be considered regular. Recent work has supported this finding, showing that attested phonological patterns can be characterized as *subregular* (Heinz, 2018), and suggesting that this is due to a categorial restriction on phonological learning (Heinz, 2010; Heinz & Idsardi, 2013; Jardine & Heinz, 2016).

Specifically, it has been argued that all phonological patterns can be characterized as either *Strictly Local* or *Tier-based Strictly Local* (TSL; Heinz et al., 2011).[4] The former level of complexity includes any pattern that bans a finite set of substrings occurring in a word, while the latter includes any pattern that does so over a *tier* of segments (i.e., certain classes of segments can be ignored by the pattern). An example of a Strictly Local pattern that commonly occurs in natural language is the typologically common restriction banning voiceless sounds after nasals (henceforth *NÇ̥; Pater, 1999). This pattern is Strictly Local since it bans any word containing the finite set of strings that results from combining all nasals with all voiceless sounds (e.g., [nt], [np], [mt], [mp], etc.). TSL patterns are also common in phonology and most harmony patterns belong to this region of the subregular hierarchy (Heinz et al., 2011; Heinz, 2018).

While Sour Grapes is still a subregular pattern, it does not reside in the same region of the subregular hierarchy as standard, attested harmony patterns (Heinz, 2018; Smith & O'Hara, 2019; Lamont, 2019b). This is because all TSL patterns can be defined by a set of banned substrings, but Sour Grapes allows almost any sequence of segments to one side of a blocker. For example, a standard backness harmony pattern in a language with three vowels in its inventory ([i], [u], and [a]) could be represented as a ban on the sequences [iu] and [ui] on the vowel tier. This would make words like *[tupi] and *[tipuka] ungrammatical, but words like [tupukati] grammatical, since the former two have [ui] and [iu] vowel bigrams in their vowel tier, while the latter only has [uu], [ua], and [ai]—all of which are allowed.

However, an analogous left-to-right Sour Grapes pattern cannot be represented so easily. The sequence [iu] would be allowed in a word like [tipuka], but not allowed in the word [tipu], because only the former has an [a] to license the disharmonic pair [iu]. Lamont (2019b) showed that Sour Grapes is located in the non-counting region of the subregular hierarchy, which is more complex than TSL.[5] This is illustrated in Figure 1.

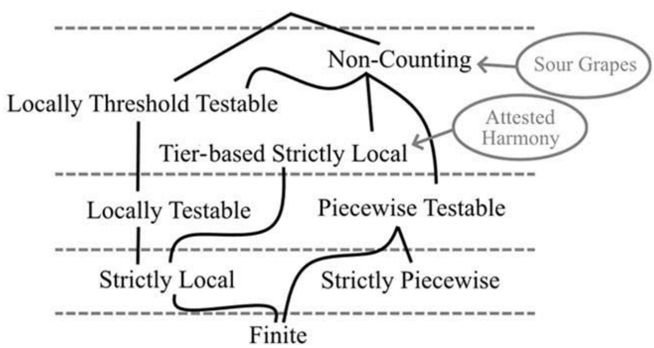

Figure 1. The Subregular Hierarchy, with the complexity of Sour Grapes and attested harmony shown.

Lamont (2019b) also showed that several non-myopic harmony patterns that have been compared to Sour Grapes in the past (e.g., tone in Copperbelt Bemba; Jardine, 2016) belong to less complex regions of the subregular hierarchy. This means that FLT provides a way to categorically differentiate between Sour Grapes and attested harmony patterns. Learning algorithms have been developed that are limited to learning TSL languages (see, e.g., Jardine & Heinz, 2016; Jardine & McMullin, 2017) and any theory that used these would correctly predict a lack of Sour Grapes in phonological typology.

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[4] *Strictly Piecewise* has also been suggested as an appropriate level of complexity to describe phonological patterns, however, see McMullin (2016) and Lamont (2018) for arguments against this.

[5] See Smith and O'Hara (2019a) for more on Sour Grapes' complexity as a function (i.e., a mapping), rather than just a language (i.e., a phonotactic restriction).

2.2. Experimental work on Sour Grapes

The learnability of Sour Grapes relative to attested harmony patterns has also been explored in experimental work, however neither of the past studies that explored the topic were able to explain the pattern's typological absence. Artificial language learning studies usually seek to show that unattested patterns are more difficult to learn or generalize in the lab than their attested counterparts (see Moreton & Pater, 2012a, 2012b for a review of such experiments). This asymmetrical difficulty if often used as an explanation for a pattern's typological absence, since a more difficult-to-learn pattern might be quickly replaced by an easier one or never properly phonologized at all (Moreton, 2008).

Lin and Myers (2010) ran an artificial language learning experiment in which two nasal harmony patterns were blocked by [s] and [k]. Their participants were native speakers of Taiwan Southern Min, a language with phonemic contrasts for nasality on both consonants and vowels, and thus were able to properly perceive a novel pattern that spread nasality. Lin and Myers (2010) trained half of these participants on an attested harmony pattern and the other half on Sour Grapes, then compared the groups' accuracies in a separate testing phase. While they *did* find a marginal difference between the accuracies in the two conditions, the difference suggested that Sour Grapes was *easier* to learn than its attested counterpart. Lin and Myers (2010) proposed that Sour Grapes' typological absence could be due to other factors, such as phonetic limitations on the kinds of diachronic changes that can occur.

Prickett (2023) presented results from a similar experiment that used vowel harmony—but instead of testing the relative learnability of Sour Grapes and an attested pattern, the experiment measured how likely participants were to learn each generalization, given ambiguous training data (for a similar methodology, see Finley, 2008). After being trained on a language that included items that were grammatical in both Sour Grapes and a standard, attested pattern, participants were asked to judge novel words. These words belonged to one of three categories: those that were grammatical in both patterns, those that were ungrammatical in both patterns, and those that were only grammatical in Sour Grapes. If participants treated the latter group as grammatical, it would show they learned a Sour Grapes pattern, but if they treated that group of words as ungrammatical, it would show they learned an attested pattern. The results in Prickett (2023) suggested that participants did neither—instead they judged words that were only grammatical in Sour Grapes as better than words that were ungrammatical in both patterns but worse than words that were grammatical in both. Prickett (2023) also presented results from computational simulations that suggested the participants' behavior was most consistent with a model that had the expressive power to represent both Sour Grapes and attested harmony, rather than a model that was categorically restricted to just one of the patterns.

3. Agent-Based Simulations

3.1. Methods

This simulations presented in this paper use a maximum entropy phonotactic learner (Hayes & Wilson, 2008; Moreton et al., 2017) to model phonological acquisition. The model's constraint set was identical to the learner in Prickett (2023) that best matched the generalization of that experiment's human participants. There were two crucial constraints in the model's grammar: one that represented Sour Grapes harmony (violated once by any word with a disharmonic sequence that wasn't licensed by a blocker) and one that represented an attested harmony pattern (violated once by any word with a disharmonic sequence of vowels). The learner also had a base set of constraints that allowed it to penalize words containing specific strings of vowels that were four or three segments long (e.g., *uiu, *iiuu, *iuui, etc.). All simulations reported here used batch gradient descent with a learning rate of .01 and initial constraint weights that were randomly sampled from 0-1.

Agent-based modeling has been shown in the past to be useful for explaining facts about phonological typology (Staubs, 2014; Hughto, 2018; Beguš, 2020), including some aspects of vowel harmony (Mailhot, 2013). The kind of agent-based modeling I used for these simulations is called *iterated learning* (Kirby & Hurford, 2002), in which language acquisition occurs over several generations, with each generation attempting to acquire the language created by the output of the previous generation, creating a "chain" of learners. While each individual chain's behavior may vary due to the randomness present in simulations, when enough chains are averaged over, general principles of a model can often be studied.

Each chain of learners in the simulations presented here started with either a categorical Sour Grapes pattern or a pattern of categorical attested harmony. Segment inventories always consisted of [a], [i], and [u], words were always 3 or 4 segments long, and the initial languages in each chain divided probability evenly across all grammatical forms. This meant that the starting language for Sour Grapes had 72 words and the starting language for attested harmony had 58. The forms present across the two patterns could be broken down into five groups (rows *i*-*v* in Table 1), with a sixth group representing words that were ungrammatical in both patterns (row *vi* in Table 1).

	Group Label	Example Word	Description
(i)	Faithful	[a u a a]	At most 1 non-blocking vowel
(ii)	Harmonic-[i]	[i i i i]	All front vowels
(iii)	Harmonic-[u]	[u u u u]	All back vowels
(iv)	Disharmonic	[u u a i]	[i]'s and [u]'s, with blocker between them
(v)	Ungrammatical-AH	[u i a i]	Disharmonic sequences, licensed by blockers
(vi)	Ungrammatical-Both	[u i i i]	Disharmonic sequences with no blockers

Table 1. The six possible kinds of words used in the simulations.

After 1000 epochs (where an epoch is a full pass through the training data), the model was used to estimate the probability of every possible string, regardless of whether the string was grammatical or ungrammatical according to the pattern it had been trained on. The next "generation" involved the same model, with its initial weights again randomly sampled from 0-1 and its training data consisting of this new probability distribution over possible words. This continued for 20 generations, with 10 full chains being simulated for each base language to ensure that the results were unlikely to be due to chance.

3.2. Results

The average probability of each of the groups of words described in Table 1, at each generation, are shown for the chains that started with attested harmony in Figure 2.

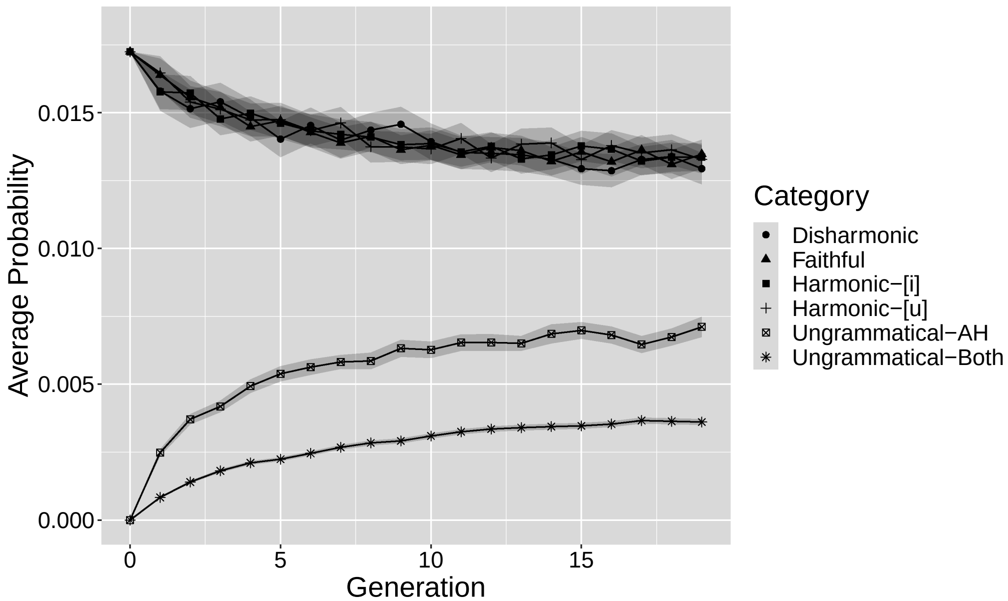

Figure 2. Results, averaged over 10 repetitions, from the agent-based simulations that had attested harmony as their initial pattern. Shaded regions show 95% confidence intervals.

The results in Figure 2 demonstrate that the attested pattern was relatively stable across the 20 generations. While the Ungrammatical-AH words (i.e., those that were allowed in Sour Grapes but banned in the attested harmony pattern) *did* gain some probability over time, a clear difference remained between them and the words that the attested pattern allowed.

Figure 3 shows the average probability for each word group by generation in the chains that started with Sour Grapes.

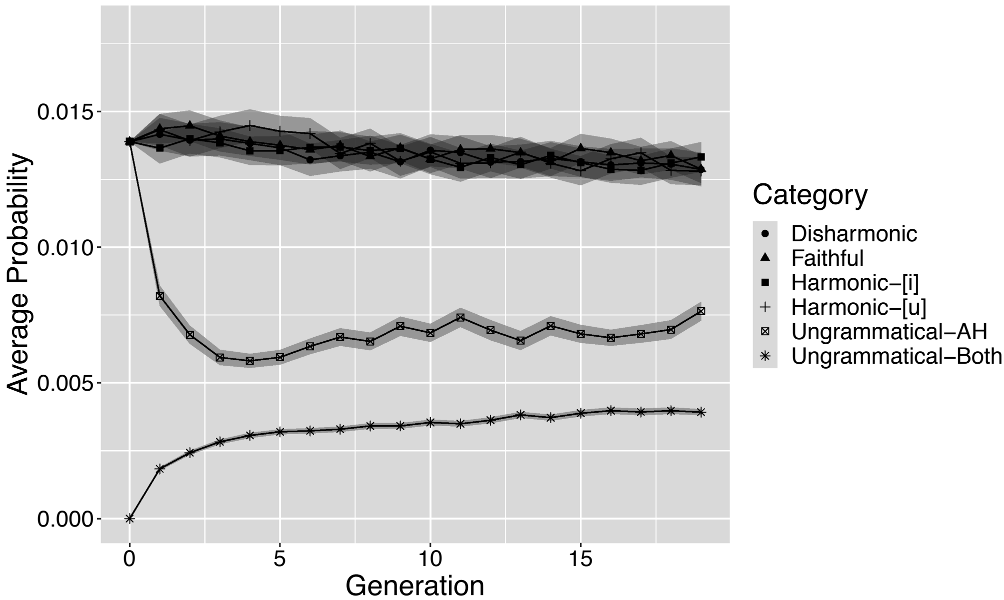

Figure 3. Results, averaged over 10 repetitions, from the agent-based simulations that had Sour Grapes as their initial pattern. Shaded regions show 95% confidence intervals.

The results shown in Figure 3 demonstrate that Sour Grapes was much less stable than its attested counterpart. After just the first generation, the Ungrammatical-AH items (i.e., those that represented the crucial difference between Sour Grapes and attested harmony) were given a much smaller probability on average than the words that were grammatical in the attested pattern. At this point, these simulations fell into the same pattern as those that started with attested harmony, with the items that were crucial for a Sour Grapes pattern remaining significantly less probable than the forms allowed by attested harmony—essentially becoming a stable attested harmony pattern, despite the initial generation of the chains being trained on Sour Grapes.

The instability of Sour Grapes in these simulations is likely caused by the subset-superset relationship between the two patterns: all the words that are grammatical in attested harmony are also grammatical in Sour Grapes, but words with licensed disharmonic sequences (i.e., the *Ungrammatical-AH* words) are only allowed in the latter pattern. Because relatively few of the words in the Sour Grapes language violate the constraint enforcing attested harmony, that constraint doesn't lose much weight over the course of learning. This causes the probability of the *Ungrammatical-AH* words (which *do* violate that constraint) to be lower at the end of the first generation than it should be, which is why the chain that begins with Sour Grapes ends up in a pattern that resembles attested harmony.

4. Discussion

Past attempts to explain Sour Grapes' typological absence have categorically limited the phonological grammar from representing the pattern—however, the results here demonstrate that this may not be necessary. A model that had the expressive power to capture both Sour Grapes and an attested harmony pattern had trouble learning the former in a way that was diachronically stable (for similar arguments using learnability to explain typology, see, e.g., Stanton, 2016).

Future work should explore the learnability of Sour Grapes as a mapping—perhaps in the form of morphological alternations, rather than a static phonotactic restriction like I did here (Lamont, 2019b). Additionally, other models that have been shown to have FLT-related biases (e.g., sequence-to-sequence neural networks; Prickett, 2021) could be tested using agent-based simulations to see if they make the same predictions as the maximum entropy model used here. And finally, the learnability of other harmony patterns that have been assumed to be unrepresentable in the phonological grammar (such as *Majority Rule*; Lombardi, 1999; Bakovic, 1999) could be tested using iterated learning to see whether their typological absence can be explained in the same way.

In the meantime, the results presented here cast doubt on whether categorical limitations to the phonological grammar are needed to explain the typological absence of Sour Grapes.

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