*Perceptually Based Constraints and Metathesis: Evidence from Artificial Grammar

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1 Introduction

The present paper explores the role of sonority and other perceptual constraints in governing syllable structure constraints. One of the most important issues in phonology today is the formalization of the phonetic grounding of markedness constraints (Hayes and Steriade 2004). Sonority constraints have been particularly controversial because there is no formalized definition of sonority, but rather several different contributing factors, such as intensity, constriction and formant transitions, that all vary depending on context (Henke, Kaisse, and Wright 2012; Wright 2004). This paper makes use of an artificial grammar learning paradigm, whereby adult English speakers were exposed to a consonant-consonant metathesis pattern that either improved sonority at a syllable boundary, or worsened sonority at a syllable boundary. Learners did not show generalization in line with sonority-based syllable contact laws, but instead showed generalization in accordance with avoidance of a voiced obstruent in coda position, thus supporting a theory of sonority and syllable contact that makes use of the interaction of perceptual cues, rather than a strict, abstract sonority hierarchy.

1.1 *Syllable Contact* Languages tend to optimize syllable boundaries so that the coda of σ1 is more sonorous than the onset of σ2 (Murray and Vennemann 1983; Vennemann 1988). For example, /el.pa/ is preferred to /ep.la/. In /el.pa/ the syllable boundary contains a sonority fall from coda to onset, but in /ep.la/, there is a sonority rise, which is why many languages (such as English) choose to parse /epla/ as /e.pla/. While syllable contact in often framed in terms of sonority (Gouskova 2004; Gouskova 2001; Parker 2003), in which there is a preference for a sonority fall across a syllable boundary, there are some issues with using sonority to predict well-formedness of syllable boundaries, particularly for segments close to each other on the sonority hierarchy. First, there is no unified definition of sonority, and languages may differ as to which definitions work best (Wright 2004). Second, sonority hierarchies vary in terms of granularity. For example, some hierarchies place voiced stops higher than voiceless fricatives, while others categorize all obstruents together (Henke, Kaisse, and Wright 2012; McGowan 2012). These various ways of categorizing sonority can lead to different predictions regarding syllable contact, and can give rise to exceptions (Clements 1990).

Alternatives to sonority as a way to characterize syllable contact constraints make use of perceptual cues, where the well-formedness of a syllable is determined by its cues (Henke, Kaisse, and Wright 2012; Wright 2004). In most cases, cues provide the same predictions as sonority, but perception-based accounts can be used to explain exceptions to sonority-based syllable contact (Clements 1990; Ohala 1990; Rose 2000). For example, obstruents have strongest cues to place, manner and voicing in the onset position, and these cues become degraded in coda position. This is especially true for voiced obstruents, explaining why voiced obstruents are often devoiced in coda position. In addition, sibilant fricatives (such as /s/ have strong perceptual cues, even in conditions where obstruents tend to be weak, explaining why sibilant fricatives are

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often considered 'exceptions' to syllable contact. Under a cue-based account, sibilants need not be analyzed as exceptions (Wright 2004).

According to McGowan (2012), syllable contact can be characterized either in terms of consonantal strength or sonority. The consonant strength scale (rhotics < laterals < nasals < voiced fricatives < voiceless fricatives < voiced stops < voiceless stops) places a higher weight to fricatives than to stops, and is similar to a course-grained sonority scale where obstruent voicing is not taken into account. The sonority-based hierarchy (glides < rhotics < laterals < nasals < voiced fricatives < voiced stops < voiceless fricatives < voiceless stops) places voiced stops above voiceless fricatives. While both scales make similar predictions for course-grained differences in segments (e.g., sonorants and obstruents), the scales make different predictions within the obstruent class. The consonantal strength scale ranks [f.b] as a better syllable contact than [b.f], while the fine-grained sonority scale ranks [b.f] as a better syllable contact than [f.b]. However, neither of these scales take into account the placement of obstruents in a word-final or coda position, which is a marked position for obstruents (e.g., as noted by the constraint *VoiObsCoda).

1.2 **VoiObsCoda* Another issue using sonority as a basis for syllable contact is that it is not clear how other constraints might interact with the sonority hierarchy, such as *VoiObsCoda, which bans voiced obstruents in a coda position (Broselow, Chen, and Wang 1998; Flack 2009). According to *VoiObsCoda, [f.b] should be less marked than [b.f], but [v.p] should be less marked than [p.v], which incurs a rise in sonority across a syllable boundary, in violation of sonority-based syllable contact laws.

The present study focuses on word initial stop-fricative clusters in English, specifically in terms of the fricatives /f/ and /v/ and the stops /p, t, k, b, d, g/. According to a course-grained sonority-based syllable contact rule, /f/ and /v/ should be preferred as codas, while stops should be preferred as onsets. According to a fine-grained sonority-based syllable contact hierarchy, where voiced obstruents are ranked as more sonorous than voiceless obstruents, /v/, /b/, /d/, and /g/ should be preferred as onsets, while /f/, /t/, /p/, and /k/ should be preferred as codas. The constraint *VoiObsCoda makes the opposite prediction as a fine-grained sonority-based constraint: voiceless obstruents /f/, /t/, /k/, /p/ should be preferred as codas, while voiced obstruents /v/, /d/, /b/, /g/ should be preferred as onsets.

The constraint *VoiObsCoda is based on the generalization that obstruents are often devoiced in word final and coda position (Flack 2009), and has been shown to emerge for speakers that do not devoice obstruents (Broselow, Chen, and Wang 1998). In addition, obstruent cues for voicing are often degraded in word final and coda position (Wright 2004), suggesting that voiced obstruents might be avoided in coda position. Support for *VoiObsCoda also comes from confusion matrices. Confusion matrices from Wang and Bilger (1973) suggest that voiced stops are more likely to be confused as voiceless stops for VC items than vice versa. For example, /b/ was confused for /p/ 75 times, while /p/ was confused for /b/ only 11 times, and /v/ was confused for /f/ 38 times, while /f/ was confused for /v/ only 20 times (p. 1256). The asymmetry between the confusability of voiced items and voiceless items was less drastic for CV items; /b/ was confused for /p/ 17 times, while /p/ was confused for /b/seven times, and /v/ was confused for /f/ 23 times, while /f/ was confused for /v/ 21 times (p. 1255). This brief look at Wang and Bilger's (1973) confusion tables suggests that voicing is more confusable in coda position than onset position for stops and fricatives (particularly the crucial /f/ and /v/ pair). If perceptually-based constraints like *VoiObsCoda are at play, then English speakers should be more likely to accept items that remove a voiced coda than create one.

1.3 *The Present Study* An increasingly promising method to tease apart questions related to phonological representation is the use of the artificial grammar learning paradigm. In an artificial grammar learning paradigm, participants are exposed to a novel, miniature version of a real language, and given test items that reflect the learning and the generalization of the pattern. For example, in the Poverty of the Stimulus Paradigm (Wilson 2006), learners are exposed to items of a language, but crucial items are held out until test, in order probe learners' inferences and generalizations about what they learned from an incomplete data set. In Wilson's (2006) study, participants were exposed to velar palatalization, either conditioned by mid or high vowels, and were then tested on the pattern with stimuli that included both mid and high vowels. Learners generalized from mid vowels to high vowels, but not vice versa, in line with the implicational universal that if palatalization is conditioned by mid vowels, it is also conditioned by high vowels. The results of this Wilson's (2006) study demonstrate learners' biases towards perceptually based phonological patterns, and provided insights into the representation of the learners' novel palatalization constraints. Several artificial grammar learning studies have shown that learners are biased to form phonologically simple, phonetically natural rules, that are maximally generalizable (Baer-Henney, Kügler, and van de Vijver 2015; Finley and Badecker 2007; Finley and Badecker 2009; Moreton 2008; Moreton, Pater, and Pertsova 2017; White 2014).

Finley (in press) showed that adult, English-speaking learners of a consonant-consonant metathesis pattern were more likely to generalize the metathesis pattern when metathesis resulted in improved syllable structure (e.g., maximized onsets). When learners were trained on a metathesis pattern that did not improve syllable structure, they generalized freely to novel syllable structures, but when learners were trained on a metathesis pattern that resulted in improved syllable structure, generalization to novel structures that did not improve syllable structure was limited. The present study extends these findings by comparing generalization to a metathesis pattern that improved syllable structure based on proposed sonority-based syllable contact laws. Finley's (in press) results predict that learners exposed to a novel metathesis pattern will generalize in accordance with improved syllable structure. If English use a fine-grained sonority hierarchy, then participants will be more likely to metathesize when it results in improved sonority-based syllable contact (e.g., /ap/ + /ve/ → [av.pe]), but if English speakers make use of *VoiObsCoda to judge syllable well-formedness, then they will be more likely to metathesize when metathesis results in a reduction of a violation of *VoiObsCoda (e.g., /av/ + /pe/ → [ap.ve]). Note that these predictions may conflict with each other, as [av.pe] results in a voiced coda, while [ap.ve] results in a sonority rise at the syllable boundary.

In the present study, adult, native English speakers were exposed to an artificial grammar in which metathesis involved either satisfaction of sonority-based syllable contact constraints, or a violation of such constraints, as shown in (1). Metathesis was induced using a triad design (Davidson, Smolensky, and Jusczyk 2004; Finley in press), in which participants heard two words and their combined form (e.g., /VC_1/ + /C_2V/ → /VC_2C_1V/). This made it possible to show the learner the input and output forms, so that it is clear to the participant that metathesis is taking place from an underlying form. Metathesis can result in improvement of syllable contact when the sonority of C_1 is higher than C_2. Metathesis results in worse syllable contact when the sonority of C_2 is higher than the sonority of C_1.

(1) Metathesis and Syllable Contact
  a. Sonority-Based Syllable Contact Improves: /ot/ + /fo/ → [of.to]; /of/ + /do/ → [od.fo]
  b. Sonority-Based Syllable Contact Worsens: /of/ + /to/ → [ot.fo]; /od/ + /fo/ → [of.do]

In addition, metathesis can also result in a change in the violation profile of *VoiObsCoda, as shown in (2). Metathesis can result in a violation of *VoiObsCoda that would not have occurred otherwise when C_1 is voiceless and C_2 is voiced (2a). Metathesis can result in removing a violation of *VoiObsCoda that would otherwise have occurred when C_2 is voiceless and C_1 is voiced (2b). When both C_1 and C_2 share the same value of voicing, then metathesis does not change the status of *VoiObsCoda, either a violation occurs (2c) or no violation occurs (2d) regardless of whether metathesis applies.

(2) Metathesis and *VoiObsCoda
  a. *VoiObsCoda Violated: /of/ + /do/ → [od.fo]
  b. Violation of *VoiObsCoda Removed: /ob/ + /fo/ → [of.bo]
  c. No Change to *VoiObsCoda (Violated): /ob/ + /vo/ → [ov.bo]
  d. No Change to *VoiObsCoda (Not Violated): /of/ + /po/ → [op.fo]

If participants learn the metathesis pattern in terms of sonority-based syllable contact constraints, they will be more likely to metathesize novel items when syllable contact is improved. However, if learners base their metathesis pattern in terms of 'cover' constraints such as a ban on voiced obstruents in coda position, then participants will be more likely to accept metathesis when metathesis results in a reduction of a violation of *VoiObsCoda.

2 Method

2.1 *Participants* Seventy-eight adult native English speakers (with no knowledge of metathesis), from Pacific Lutheran University participated for course credit. Of these 78 participants, seven participants were excluded because they were not native English speakers, and one participant was excluded due to experimenter error. An additional eight participants were excluded after analysis because they failed to choose the metathesis items on at least 50% of the Old items; a total of 62 participants were included in the final analyses.

2.2 *Stimuli and Exposure* The experiment consisted of two phases: exposure and test, all of which were presented in Psyscope X (Cohen et al. 1993). The exposure phase consisted of 24 sets of triads repeated five times each, in a different random order each time. The triads were based on Davidson et al. (2000) and Finley (in press)'s triad design: (e.g., /VC_1/ + /C_2V/ → /VC_2C_1V/)/. In each case, the consonant was either a stop (/p, t, k, b, d, g/) or a labiodental fricative (/f, v/). The vowels were from the set /e, i, o, u, a/. A female native English speaker with no knowledge of the experimental hypothesis produced all items on a Marantz portable recorder in a sound-attenuated space. Stress in the bisyllabic items was produced on the first syllable. All sounds were edited using Praat (Boersma and Weenink 2015) and normalized for average intensity of 70Hz.

Participants were randomly assigned to one of four training conditions: Coda-v, Onset-v, Coda-f, and Onset-f, as defined by the type and location of the labiodental fricative as a result of metathesis. In the Onset conditions, metathesis resulted in the fricative becoming an onset, meaning that the fricative (/v/ or /f/) was always C_1. In the Coda conditions, metathesis resulted in the fricative becoming a coda, meaning that the fricative (/v/ or /f/) was always C_2. The Onset conditions resulted in improved syllable contact, as metathesis creates a syllable boundary with a fall in sonority (fricative to stop). In all conditions, the stops were a mix of voiced and voiceless stops, but the fricative was always the same (e.g., always /f/ or always /v/). This means that a violation of *VoiObsCoda could be induced in both Coda-f and Onset-f, when the stop is voiced, and can be induced in Onset-v when the stop is voiceless. However, in Coda-f, *VoiObsCoda is never violated, and is improved when the stop consonant is voiced.

(3) Examples of training stimuli

Condition	Examples	Syllable Contact	*VoiObsCoda
Coda-v			
Voiceless Stop	ep + vo → ev.po	Improves	Induces Violation
Voiced Stop	eb + vo → ev.bo	Improves	No Change
Onset-v			
Voiceless Stop	ev po → ep.vo	Worsens	Removes Violation
Voiced Stop	ev bo → eb.vo	Worsens	No Change
Coda-f			
Voiceless Stop	ep + fo → ef.po	Improves	No Change
Voiced Stop	eb + fo → ef.bo	Worsens	Removes Violation
Onset-f			
Voiceless Stop	ef po → ep.fo	Worsens	No Change
Voiced Stop	ef bo → eb.fo	Improves	Induces Violation

Based on the results of Finley (in press), participants should be more likely to learn a general metathesis pattern (e.g., one that applies in all cases) when metathesis does not reduce markedness or syllable contact. This suggests that participants in the Onset-f condition should be most likely to form a general metathesis rule, as metathesis in this condition both worsens syllable contact and induces violations of *VoiObsCoda. This also suggests that participants in the Coda-f condition should be least likely to form a general metathesis pattern, since this metathesis in this condition both improves syllable contact and (in cases of voiced stops), can remove a violation of *VoiObsCoda. The relative generality of Coda-v and Onset-v should depend on the relative ranking of sonority-based syllable contact and violations of *VoiObsCoda, as

Coda-v improves syllable contact but can cause a violation of *VoiObsCoda, while Onset-v worsens syllable contact, but can remove a violation of *VoiObsCoda.

2.3 *Test* Following the exposure phase, participants were given a two-alternative forced-choice task to assess their learning and generalization of the metathesis pattern. The two-alternative forced choice test required participants to compare two triads: one with no change, the other resulting in metathesis; both triads were identical in all other respects. Examples of test items can be found in the Table in (4). Note that while the metathesis options are always presented first in this table, items were counter-balanced as to whether the metathesis option occurred first or the no-change option occurred first.

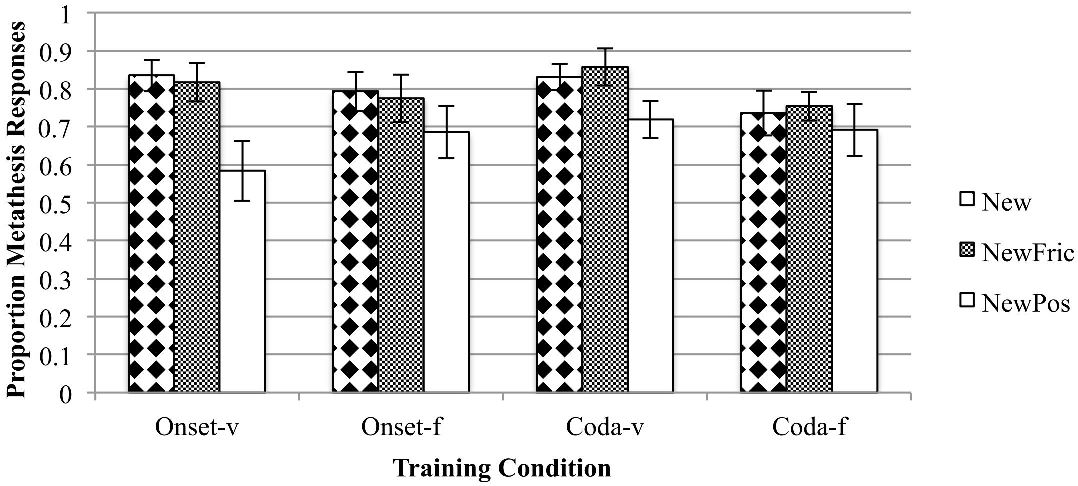
(4) Examples Test Stimuli (Metathesis vs. No Change)

	Coda-v	**Onset-v**	**Coda-f**	**Onset-f**
Old/New	ep + vo → evpo vs. ep + vo → epvo	ev po → epvo vs. ev po → evpo	ep + fo → efpo vs. ep + fo → epfo	ef po → epfo vs. ef po → efpo
New-Fricative	op + fu → ofpu vs. op + fu → opfu	of + pu → opfu vs. of + pu → ofpu	op + vu → ovpu vs. op + vu → opvu	ov + pu → opvu vs. ov + pu → ovpu
New-Position	ov + pu → opvu vs. ov + pu → ovpu	op + vu → ovpu vs. op + vu → opvu	of + pu → opfu vs. of + pu → ofpu	op + fu → ofpu vs. op + fu → opfu

There were four types of test items, with 12 of each type. All items were presented in a random order. Old items were items that were drawn directly from the training set, and were used to exclude participants from analysis Any participant that failed to score more than 50% on the Old items was excluded, with the logic that if a participant fails to apply metathesis to items heard in the training set, then it is unclear how to interpret their responses to novel items. New items were items that were similar to the training set in that they followed the same pattern as items in training (e.g., New items in the Coda-v condition resulted in /v/ in the coda position following metathesis). New Fricative items contained the fricative that was not heard in training, but in the same position (onset or coda) (e.g., New Fricative items in the Coda-v condition resulted in /f/ in the coda position following metathesis). New Position items contained the same fricative as the training condition, but resulted in the fricative in a new position (onset or coda) as the training (New Position items in the Coda-v condition resulted in /v/ in the onset position following metathesis).

2.4 *Results* Means and standard errors are presented in the figure in (5). Only novel items were included in the statistical analyses. Eight participants (of 70) were excluded because they failed to metathesize to more than 50% of Old items. Of the eight participants, two were in the Coda-v condition, one was in the Coda-f condition, two were in the Onset-v condition, and three were in the Onset-f condition. Raw data and other associated files can be found on the Open Science Framework (OSF) at: https://osf.io/gzdt3.

(5) Means and Standard Errors by Condition and Test Items



Statistical analyses were conducted using mixed logistic regressions in R (R Development Core Team 2011) based on the maximal model that would consistently converge (Barr et al. 2013). The table in (6) shows the predictions for New Position items based on each condition for voiced and voiced stops in the New Position items in terms of sonority-based syllable contact and *VoiObsCoda.

(6) Predictions of Generalization for New Position Items

	Training Condition	Syllable Contact	*VoiObsCoda
Coda-v	**New Position**		
Voiceless Stop	av po → ap.vo	Worsens	Improves
Voiced Stop	av bo → ab.vo	Worsens	No Change
Onset-v	**New Position**		
Voiceless Stop	ap vo → av.po	Improves	Worsens
Voiced Stop	ab vo → av.bo	Improves	No Change
Coda-f	**New Position**		
Voiceless Stop	af po → ap.fo	Worsens	No Change
Voiced Stop	af bo → ab.fo	Improves	Worsens
Onset-f	**New Position**		
Voiceless Stop	ap fo → af.po	Improves	No Change
Voiced Stop	ab fo → af.bo	Worsens	Improves

The New Position items for Coda-v improve *VoiObsCoda but worsen sonority-based syllable contact, while the New Position items for Onset-v improve sonority-based syllable contact but worsen *VoiObsCoda. In the Coda-v condition, sonority always decreases across the syllable boundary, thereby improving syllable contact. In the Onset-v condition, sonority always increases across the syllable boundary, thereby worsening syllable contact If participants learn that metathesis applies in order to improve syllable contact, then participants in the Coda-v condition, where syllable contact improves, will be less likely to generalize to New Position items than participants in the Onset-v condition. This was not confirmed, as generalization to New Position items for the Coda-v condition was, in fact, significantly *lower* than generalization to New Position items in the Onset-v condition (β=0.91, z =3.61, $p < 0.001$). In fact, the results support the hypothesis in which participants learned a pattern based in *VoiObsCoda, as New Position items in the Coda-v condition either result in an improvement of *VoiObsCoda or no change, while New Position items in the Onset-v condition either result in a violation of *VoiObsCoda or no change. Because the predictions for Coda-f and Onset-f depended on the voicing of the stop, the voicing of the stop was added as a parameter to the model, so that the base for comparison was for New Position items that contained a voiced stop. There was a significant difference between Coda-f and Onset-f for voiced items (*ß*=0.89, z =2.07, p = 0.038) such that there were more metathesis responses in the Onset-f condition than in the Coda-f condition, which is predicted by the *VoiObsCoda, and the opposite prediction of the sonority-based syllable contact account.

The table in (7) shows the outcomes of metathesis in terms of sonority and *VoiObsCoda across each training condition for New Fricative items.

(7) Predictions of Generalization New Fricative

	Training Condition	Syllable Contact	*VoiObsCoda
Coda-v	**New Fricative**		
Voiceless Stop	ap fo → af.po	Improves	No Change
Voiced Stop	ab fo → af.bo	Worsens	Improves
Onset-v	**New Fricative**		
Voiceless Stop	af po → ap.fo	Worsens	No Change
Voiced Stop	af bo → ab.fo	Improves	Worsens
Coda-f	**New Fricative**		
Voiceless Stop	ap vo → av.po	Improves	Worsens
Voiced Stop	ab vo → av.bo	Improves	No Change
Onset-f	**New Fricative**		
Voiceless Stop	av po → ap.vo	Worsens	Improves
Voiced Stop	av bo → ab.vo	Worsens	No Change

New Fricative items always resulted in improved sonority-based syllable contact in the Coda-f condition, while New Fricative items could result in worsened sonority-based syllable contact in the Coda-v condition. Thus, if learners used a sonority-based syllable contact rule, then should be significantly more metathesis responses to New Fricative items for Coda-v than Coda-f. However, there were significantly more metathesis responses to New Fricative items between the Coda-v and Coda-f conditions, the *opposite* of the predicted result (*ß*=0.69, z =2.67, p = 0.0075). This result supports the hypothesis that learners make use of *VoiObsCoda, as New Fricative items in the Coda-v condition produce /f/ in the coda, resulting in a potential removal of a violation of *VoiObsCoda, while New Fricative items in the Coda-f condition produce /v/ in the coda, resulting in a voiced coda, producing violations of *VoiObsCoda. Because the predictions for Coda-v and Onset-v depend on the voicing of the stop, the voicing of the stop was added as a parameter to the model, so that the base for comparison was for New Fricative items that contained a voiced stop. There was no significant difference between Coda-v and Onset-v for voiced items (*ß*=0.52, z =1.22, p = 0.21), but Coda-v was numerically higher such and the opposite prediction of the sonority-based syllable contact account.

To further explore the role of sonority in producing metathesis responses, all items (excluding Old items) were coded in terms of the sonority difference between the onset and the coda, following metathesis, with voiced fricatives worth 4, voiced stops worth 3, voiceless fricatives worth 2 and voiceless stops worth 1. The point value of the onset was subtracted from the point value of the coda. For example /ap.ve/ was scored as a -3 because /p/ is worth 1 and /v/ is worth 4 (1- 4 = -3). A mixed-effects model was run with random slopes and intercepts for subjects and items; the model was not significant, and was slightly negative (*ß*=-0.037, z =-0.70, p = 0.49). To further investigate, the sonority was recoded to be categorical: positive for the items with positive scores (1 and 3), and negative for items with negative scores (-1 and -3). This was run in an additional model, with random slopes and intercepts for items. This model was significant, but in the opposite direction of what would be predicted by sonority (negative sonority produced more metathesis responses than positive sonority) (*ß*=0.21, z =2.03, p = 0.043). This further suggests that participants followed metathesis in the opposite pattern of sonority. Finally, responses were coded in terms of a more course-grained sonority profile, where all stops were coded as less sonorous than all fricatives, regardless of voicing. This model, which contained random slopes and intercepts for items and subjects, was not significant (*ß*=0.25, z =1.28, p = 0.20). These results suggest that if sonority plays a role in determining metathesis responses, metathesis was applied only when sonority resulted in worse syllable contact.

To further explore the role of *VoiObsCoda in metathesis responses, all items were coded in terms of whether *VoiObsCoda was violated as a direct result of metathesis (Voiced Coda, mean = 0.74, SD = 0.44), removed a violation of *VoiObsCoda (Voiceless Coda; mean = 0.81, SD=0.39), or did not change the violation profile of *VoiObsCoda (No Change; mean = 0.75, SD = 0.43). The model with random slopes and intercepts for items was only marginally significant between Voiceless and Voiced items (β=0.28, z =1.91, p = 0.057), and between Voiceless and No Change items (β=0.22, z =1.73, p = 0.084). This suggests that participants' use of metathesis to decrease violations of *VoiObsCoda may be tied more specifically to the training conditions that the learner is a part of, and more research is needed to better understand specifically how learners make use of *VoiObsCoda in the metathesis pattern.

Finally, the interaction between sonority and *VoiObsCoda was explored, with the hypothesis that when both *VoiObsCoda and sonority was improved, that participants would be more likely to select the metathesis response. A model was created with the interaction of Voiceless items and Positive sonority items, with random intercepts for items (more complex models failed to converge). There was no significant difference between Positive and Negative sonority for Voiceless items (β=1.09, z =1.05, p = 0.29), suggesting that Voiceless items were not influenced by sonority in the direction predicted by the sonority-based syllable contact law.

3 Discussion

This study investigated role of sonority and voicing in generalization of metathesis. English-speaking participants were exposed to a consonant-consonant metathesis pattern in which a stop and a fricative changed places. Participants were exposed to one of four metathesis conditions, based on the position of the fricative. In the Onset-f condition, /f/ always became an onset as a result of metathesis. In the Onset-v condition, /v/ always became an onset as a result of metathesis. In the Coda-f condition, /f/ always became a coda as a result of metathesis. In the Coda-v condition, /v/ always became a coda as a result of metathesis. These various placements of the fricative resulted in different levels of improvement or worsening of the syllable structure. For example, placing /v/ in coda position improves a sonority-based syllable contact constraint because /v/ is the most sonorous obstruent in the experiment (compared to, for example, a voiceless stop). However, placing /v/ in the coda position necessarily induces a violation of *VoiObsCoda. If participants learn that metathesis applies to improve syllable-structure, learners will be more likely to generalize that pattern to cases where syllable structure constraints are improved. However, none of the comparisons that made reference to sonority supported this hypothesis, and many comparisons were significant in the opposite direction. Importantly, many of the predictions made by sonority were the opposite for an account in which learners metathesized in order to improve the violation profile for *VoiObsCoda. These suggest that learners made use of *VoiObsCoda rather than sonority-based syllable contact constraints.

It is important to recognize that much of the analyses presented in this paper were exploratory, and were not planned at the design of the experiment. More research in which the implications for *VoiObsCoda and sonority are clearly controlled for and where planned comparisons are made are needed to fully verify the findings presented in this paper. However, there is reason to be optimistic about the results of the present study. First, preliminary results of a study directly controlling for *VoiObsCoda show the same trends as in the present study. Second, all of the results pointed to the direction that participants were responding in terms of *VoiObsCoda rather than a sonority-based syllable contact account, suggesting that it is unlikely that learners made use of sonority in the way that is suggested by a fine-grained sonority hierarchy.

Alternative accounts of the sonority hierarchy make use of perceptual cues to better understand syllable structure constraints. Cue-based accounts may be used to explain the results of the present study. Wright (2004) notes that the cues for frication are stronger than stops in coda position, cues for voicing, particularly for non-sibilant fricatives and stops are very weak in coda position. Thus, while, in general, fricatives may have more robust cues in coda position, non-sibilant fricatives and stops have weak voicing cues in coda position, suggesting that English speakers may be biased against all non-sibilant voiced obstruents in coda position.

The present study made use of a fine-grained sonority hierarchy, comparing differences within obstruents. However, the sonority hierarchy can take on many levels of granularity (Henke, Kaisse, and

Wright 2012), from all obstruents in one category, to voicing falling into different categories. Analyses that make use of the sonority hierarchy often specify the minimum difference in sonority required (e.g., a minimum of two steps on the hierarchy) (Gouskova 2001). Thus, it is entirely possible that the predictions made by the sonority-based syllable contact account were simply too fine-grained for the English speakers used in this study. However, the differences in granularity of the sonority hierarchy across languages is one reason why it may be prudent to use cue-based constraints, so that differences in sonority based on a variety of components (e.g., constriction, formant transitions, intensity) can be weighted amongst other types of constraints (e.g., *VoiObsCoda). This would create an account of the correct predictions of the sonority-based syllable contact law, as well as the exceptions, without ad hoc changes to the hierarchy, or language-specific differences in granularity of the hierarchy. Different cue weights could be derived (e.g., through constraint ranking or weighting of constraints). Future research is needed to better understand how a cue-based account of sonority and syllable contact might be integrated into a formal (e.g., Optimality Theory; Prince and Smolensky 2004) account of syllable structure constraints.

While the present paper has emphasized perceptual cues to explain patterns found from sonority-based syllable contact constraints, it is important to recognize that production may play a critical role in the findings of the present experiment. While cues for voiced obstruents are weak in the coda position compared to the onset position (Wright 2004), production of voiced obstruents is also degraded in coda position, particularly when followed by another obstruent (Davidson 2016). Davidson (2016) showed that production of voicing differs for stops and fricative depending on the context; stops were more likely to be voiced in word final position than fricatives. It is very likely that the differences in production in various contexts interact with perceptual cues. Because both production and perceptual cues are highly context-specific, teasing apart how these cues are reflected in the grammar is a task that goes beyond a single experiment or study, and much more research is needed to fully understand how perception and production interact with categorical phonological patterns like the metathesis pattern discussed in the present paper.

The present paper explored the role of syllable structure constraints in generalizing a novel metathesis pattern. Participants extended the metathesis pattern in accordance with removing a violation of *VoiObsCoda, rather than the predictions based on a fine-grained sonority-based syllable contact laws. The results support the interaction of various perceptual cues and constraints on syllable structure.

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