Phonological markedness effects in sentence formation*

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Abstract

Earlier research has found that phonological markedness constraints (for example, against stress clash or sibilant sequences) statistically influence speakers' choices between particular syntactic constructions and between synonymous words. In this study, we test phonological constraints not just in particular cases, but across the board. We employ a novel method that uses a MaxEnt grammar to model the distribution of WORD BIGRAMS (consecutive two-word sequences) and how this distribution is influenced by phonological constraints. Our study of multiple corpora indicates that several phonological constraints do indeed play a statistically significant role in English sentence formation. We also show that by examining particular subsets of the corpora we can diagnose the mechanisms whereby phonologically marked sequences come to be underrepresented. We conclude by discussing modes of grammatical organization compatible with our findings.

Keywords: markedness, phrasal phonology, syntax-phonology interface, grammatical architectures, maximum entropy grammars

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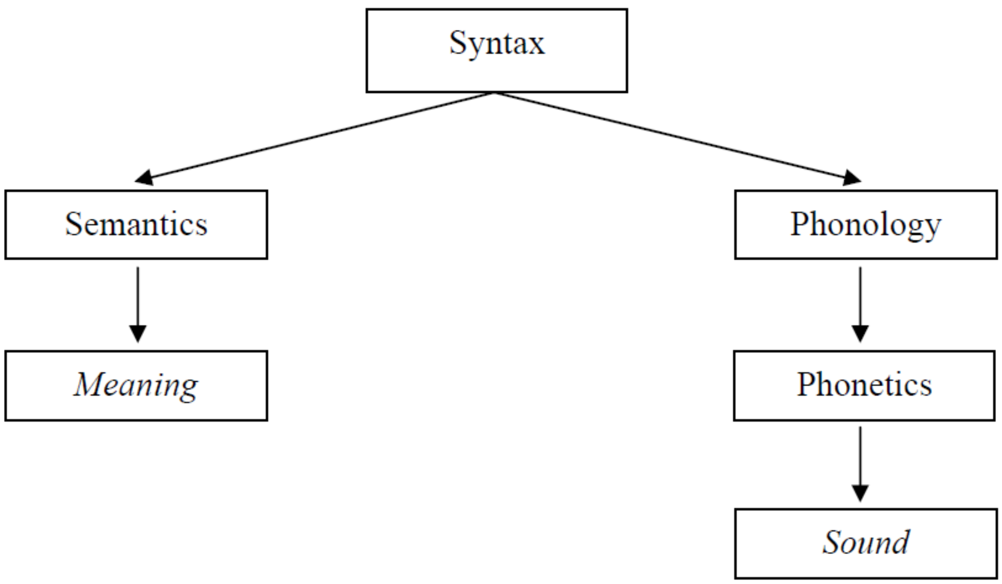
1. Goals and setting

The focus of this paper is how different domains of linguistic knowledge — here, syntactic, phonological, and lexical — interact in the creation of sentences. An influential proposal for how these domains interact is the componential feed-forward model, laid out in Chomsky (1965:16) and shown in Figure 1. This model places the syntactic component at the core of the grammar, with its output transmitted to two interpretive components, which derive output representations for meaning and sound.

Figure 1: A schematic depiction of the feed-forward model



A crucial empirical prediction of this model is that “late” components in the derivation — for us, phonology — cannot have an influence on “early” components such as syntax. This claim is sometimes called the “principle of phonology-free syntax” (Zwicky and Pullum 1986)

The feed-forward model is widely taught in introductory courses (for example, our own), but the empirical challenges raised against it have been substantial. For instance, the syntax of a language often offers more than one way to express a given meaning, and it can be shown that speakers’ choices between alternative constructions are sometime phonologically motivated. For example, Shih and Zuraw (2017, 2018) studied two parallel noun-adjective constructions in Tagalog: {Adj. *linker* Noun} and {Noun *linker* Adj.}, where *linker* is one of two contextually determined allomorphs *na* or *-ng*. Using corpus data, they showed that speakers tend to choose between these options in ways that avoid violating certain phonological markedness constraints: *[+nasal][+nasal], *HIATUS, and *NC̥, all of which are active elsewhere in the language’s phonology. Similar instances of phonologically-biased syntactic choice have been detected for the English dative alternation (*give X to* Y vs. *give Y X*; Anttila et al. 2010, Shih and Graffmiller 2011, Shih 2017a), the genitive alternation (*X’s Y*, *Y of X*; Shih et al. 2015, Ryan 2018), and the conjunct-order alternation (*X and Y*, *Y and X*; Benor and Levy 2006, Shih 2017a, Ryan 2018).

Other forms of evidence have been put forth. For instance, the linear ordering of clitics is argued to depend in part on phonological factors (Zec and Inkelas 1990, Chung 2003). The notion of weight, governing Heavy NP Shift, Topicalization, and other aspects of word order, has been argued to be at least partly phonologically defined (Zec and Inkelas, Shih and Grafmiller 2011, Ryan 2018). Along with Zec and Inkelas, Agbayani and Golston have argued for movement operations (for instance, Japanese long-distance scrambling) that apply to phonological, not syntactic, constituents (Agbayani and Golston 2010, Agbayani et al. 2015).

To accommodate such phenomena, some formal models bifurcate the syntax, establishing a privileged core which is phonology-free but performs only a subset of the work of actually arranging words into sentences, leaving other aspects of linearization to separate mechanisms. Such approaches would include the work of Agbayani and colleagues just cited as well as Embick and Noyer (2001). Our data do not bear, as far as we can tell, on the validity of such models. However, the approach of isolating a phonology-free core of the syntax does have the potential to obscure what is meant by "phonological effects in syntax," ruling out their existence more or less by definition (Anttila 2016:130). To keep our purpose clear, we use the phrase "sentence formation," designating whatever grammatical apparatus is employed, in any framework, to derive complete, observable sentences.

"Sentence formation" would also include word choice, which also appears to be guided by phonological constraints. Schlüter (2005, 2015) has demonstrated that, given a synonym pair, speakers tend to select the word that creates fewer phonological constraint violations in its local syntactic context. Her evidence comes from the distribution of historical English lexical doublets like *worse* and *worser*, which are gradiently deployed to avoid violations of *CLASH (stress on adjacent syllables). Schlüter and Knappe (2018) have obtained similar results for modern synonym pairs such as *glad*/*happy*.

A characteristic of the cases just cited is that the phonology enforces a *gradient* preference among competing syntactic variants, a property we will see below in our own data. Yet the pattern is not always gradient; analysts have suggested cases in which utterances are fully ungrammatical and part of the reason is the violation of a phonological constraint. For instance, Anttila (2016), drawing on earlier work, offers such an account for the ungrammaticality of sentences like **Pat gave Chris it*. Further instances may be found in Zec and Inkelas (1990), Harford and Demuth (1999), and Agbayani et al. (2015).

The literature that critically addresses the feed-forward model appears to be both vast and fragmented among distinct research communities (Anttila 2016:133), and it may be that there are few participants who fully aware of all the parallel lines of research. The absence of a consensus theoretical framework for such work has surely contributed to this fragmentation. For further access to this literature we recommend the surveys (incorporating specific proposals) by Anttila (2016), Shih (2017a) and Ryan (2018).

We address the question of theoretical framework at the end of this article. Our main purpose, however, is empirical: we seek to expand the set of relevant phenomena and offer a novel research method. In previous research, it has been the norm to choose some specific area to investigate; e.g. a particular choice between competing syntactic constructions or lexical items. This approach is sensible, since it offers closely controlled comparisons. However, we feel it may be appropriate to complement this work with a broader, scaled-up approach. For our project, we have devised a means of testing the entire content of a body of text, examining the effects of multiple phonological constraints at the same time. Our method, outlined below, involves analyzing the complete set of WORD BIGRAMS (sequences of two consecutive words) from a text. We employ a formal model implemented as a Maximum Entropy grammar (Smolensky 1986, Goldwater and Johnson 2003) that assesses the degree to which a range of phonological constraints were respected in the creation of these bigrams.

What are the advantages of such a broad-based approach? First, the simplicity of our method means it is widely applicable, permitting us to test essentially any phonological constraint whose violations can arise across word boundaries. Second, since the method is not tied to particular words or constructions, it can be applied to very large quantities of text, which can provide it with the statistical power needed to detect effects too subtle to be found by other means. Lastly, we demonstrate that our method is sufficiently flexible that it can be used to go beyond merely revealing the existence of phonological effects in sentence formation, and make a start at diagnosing the mechanisms by which these effects arise.

Applying our method, we confirm earlier results in finding pervasive effects of phonological optimization: in both speech and writing, sentences gradiently respect phonological markedness constraints. Our findings also suggest that this pattern is the result of multiple causes. A large fraction of the phonological effects are due, as earlier literature suggests, to choices made between competing syntactic constructions. But we attribute another large portion to a different source: extending ideas of Martin (2011), we suggest there is a preference for lexical listing of phonologically-unmarked fixed phrases. In our final section, we discuss implications of the work, including the forms of grammatical architecture that are compatible with our findings.

2. Constraints studied

As noted above, we treat a text as a sequence of WORD BIGRAMS; that is, overlapping pairs of consecutive words. For example, in the preceding sentence the first three word bigrams are [*as noted*], [*noted above*], and [*above we*]. When a speaker or writer concatenates two words to form a bigram, there is a possibility that a phonological constraint violation will be created at the juncture; for example, if *book* is concatenated with *concludes*, this creates a violation of the phonological constraint *GEMINATE (see below), as shown: [bʊk kənkludz].

Using English data, we examined violations of nine phonological constraints. These were chosen by two criteria. First, we favored constraints that are only seldom violated within the confines of a word. We also took into account the typological status of constraints, relying on the research literature. We judged that by following these criteria we would have the best chance of locating constraints that would have an effect at the phrasal level. To test for word-internal constraint strength we employed the UCLA Phonotactic Learner (Hayes and Wilson 2008), taking a constraint to be strong if this algorithm assigned it a substantial weight. The weights we obtained in our word-internal baseline modeling may be viewed in the Supplemental Materials for this article.

2.1 Stress Clash Constraints. The constraint *Clash plays a major role in constraint-based analysis of stress, and it is well supported for English, for instance in explaining the patterns of stress retention in “cyclic” stress patterns. Thus, *assimilation* [əˌsɪməˈleɪʃən] retains a secondary stress on its second syllable inherited from *assimilate* [əˈsɪməleɪt], but *provocation* [ˌpɹɑvəˈkeɪʃən] fails to retain the stress of *provoke* [pɹəˈvoʊk], since it would clash with the main stress on the penult. For a detailed analysis, see Pater (2000). The effects of *Clash on sentence formation have already been supported by the English corpus study of Temperley (2009), and our results will be seen to confirm his findings.

The more specific constraint *Iambic Clash is violated when a rising sequence of stress immediately precedes a still stronger stress, as in the phrase *maroon sweater* ([məˌrun ˈswɛɾɚ]). Exceptions to *Iambic Clash within words in English are very rare, and the relevant pronunciations are often not shared by all speakers. For instance, one of the authors of this article says *electronic* [əˌlɛkˈtɹɑnɪk] with an iambic clash, thus retaining the base stress pattern of *electron* [əˈlɛkˌtɹɑn]; the other author says *electronic* [ˌilɛkˈtɹɑnɪk], with the iambic clash repaired. Within phrases, the well-known “Rhythm Rule” (Liberman and Prince 1977 et seq.) removes *Iambic Clash violations, as in *unkind* [ʌnˈkaɪnd], but *unkind people* [ˌʌnkaɪnd ˈpipəl]. The research literature on *Iambic Clash has an unusual time depth; see Fijn van Draat (1910), Bolinger (1965). The phrasal effects of *Iambic Clash have also been studied with more modern methods (i.e., statistical analysis of a digital corpus) by Hammond (2016); his results largely match what we describe below.

2.2 Bans on Long Clusters. Long consonant clusters are well known to be phonologically marked in general; and for English our word-internal modeling indicates they are underrepresented in the lexicon. For ease of assessment, in our constraints we did not attempt to include syllable structure, but simply set up two linear constraints, *Triple Consonant Cluster as well a more specific version, *Triple Obstruent Cluster, that we expected to be the stronger of the two. For our purposes these constraints assess violations only for sequences of the form *C#CC or *CC#C, since *#CCC and *CCC# have no independent bearing on bigram formation.

2.3 *Sibilant Clash. Like many languages, English avoids consecutive sibilants within words; there are absolutely no monomorphemes like “*kessha*” *[kɛsʃə]; and even affixed forms like *misshapen* [mɪsʃeɪpən] are rather unusual. Our analysis thus includes the constraint *Sibilant Clash, which we state formally as *[+strident]$\begin{bmatrix}\text{+strident}\\ \text{+continuant}\end{bmatrix}$. Note that this constraint is formulated so as not to be violated by sequences in which the second member of the cluster is an affricate; this is appropriate because in fact English has many words of this type, such as *question* [ˈkwzɛstʃən].

2.4 *Geminate. English strictly avoids geminates (identical consonant sequences) within monomorphemes; for example, to pronounce the Italian word *latte* ‘milk’ with a geminate [tt], as in the original, would be inconceivable for English speakers. Only a few affixed forms, such as *unknown* [ʌnnoʊn], include geminates. Importantly, Martin (2011) demonstrated that geminates are underrepresented even in English compounds; cases like *bookkeeper* do exist, but they are rare with respect to the statistical baseline computed by Martin. Martin's explanation for this underrepresentation will be adopted and extended below.

2.5 *HIATUS. This constraint is violated by consecutive vowels. *HIATUS (or its near-equivalent *NO ONSET; McCarthy and Prince 1993/2004:34-37) has a substantial pedigree in Optimality Theory and plays a role in the phonology of many languages. Vowel sequences do occur within English words (e.g. in *media* [ˈmidi̯ə]) but nonetheless in the modeling work mentioned above, *HIATUS violations emerged as statistically underrepresented.

2.6 *BAD SONORITY. The Syllable Contact Law (Hooper 1976, Murray and Vennemann 1983), militates against heterosyllabic clusters to the extent that their initial coda consonant has lower sonority then the following onset consonant; in English, any CC cluster formed across word boundaries will consist of a coda followed by an onset and thus fall under the scope of this Law. We set up the constraint *BAD SONORITY, whose violates are computed by subtracting the sonority of the violated when the first of two consonants across a word break has lower sonority than the second on the scale *obstruent - nasal - liquid - glide*. As our modeling indicates, violations within words are moderately underrepresented.

2.7 *NC̥. This constraint bans voiceless consonants after nasals. It is *not* enforced within English words (in our word-internal testing, we found no effect at all), but its typological pedigree (Pater 1999) led us to test its applicability at the phrasal level. In the hope of avoiding statistical confounds from the effect of other constraints, we adopt a very narrowly defined version of *NC̥, banning only homorganic *nasal* + *stop* sequences; that is, [mp, nt, ŋk].

Summing up, (1) gives the full list of constraints we tested.

(1) *List of phonological constraints tested*

a. *CLASH
b. *IAMBIC CLASH
c. *TRIPLE OBSTRUENT CLUSTER
d. *TRIPLE CONSONANT CLUSTER
e. *SIBILANT CLASH
f. *GEMINATE
g. *HIATUS
h. *BAD SONORITY
i. *NC̥

3. Word bigrams as a basis for detecting the effects of phonological constraints

To test these constraints, a method is needed that can digest all the word bigrams of a text corpus and determine whether they collectively underrepresent phonological constraint violations. To start, suppose that the corpus under examination consists of the six canonical novels of Jane Austen. For present purposes, we adopt the (philistine) idealization of Austen as a stochastic device that emits word bigrams; thus we seek to model the frequency with which each bigram is emitted. The Austen corpus is 723,214 words long and so (ignoring some trimming back to be carried out below) there are 723,213 bigrams.

A sensible starting point is to assume that each word is emitted with a probability matching its corpus frequency. For instance, in the corpus, *Elizabeth* occurs 454 times, and hence is emitted with a probability of 454/725,374 = 0.00063. *Bennet* occurs 291 times, thus with a probability of 454/725,374 = 0.0004. If one knows the probabilities of both words in a bigram, then the probability of that bigram can be computed as their product; so that the expected rate for the bigram *Elizabeth Bennet* in the Austen corpus is 454/723,214 × 291/725,374 = 0.00000025, corresponding to a predicted text frequency of 0.18.

The observed frequency of a particular bigram will only seldom be identical to the expected value as just computed. For instance, the bigram *Elizabeth Bennet* actually occurs 6 times in the Austen corpus, 33 times the expected frequency. This is hardly surprising, since *Elizabeth Bennet* is the full name of the heroine of Austen's novel *Pride and Prejudice*. But by considering *aggregated* data, it is possible to abstract away from such factors and hope to find broader principles governing the bigram frequencies. In particular, we focus on possible effects of the phonological constraints given earlier: our estimate of the degree to which Jane Austen respects the phonological constraints when she emits bigrams will be based on the degree of improvement in our ability to predict her bigram frequencies that is obtained when we include the phonological constraints in a statistical model. Below, we discuss how we worked out this scheme in concrete terms.

4. Choice of framework

We need a formal framework for our work which has certain properties: it must make use of constraints, and it must be able to assign a probability to every possible bigram, so that we can check its predictions against the corpora. Further, the model should be founded in secure mathematical principles, it should be amenable to statistical significance testing, and the equipment and software needed to carry out the necessary computations should be available. The MAXIMUM ENTROPY (MaxEnt) framework (Smolensky 1986, Della Pietra et al. 1997, Goldwater and Johnson 2003 et seq.) fully satisfies these criteria.[2]

4.1 Summary of MaxEnt

MaxEnt may be construed as a variant of standard Optimality Theory (Prince and Smolensky 1993/2004). However, unlike OT, MaxEnt outputs not a set of winners, but rather a set of probabilities, one for each output candidate. In addition, the relative strength of constraints is specified not by ranking them but by assigning each a real number, referred to as its weight.

The core of MaxEnt is formula (2), which takes as inputs the set of candidates, constraints, constraint violations, and weights, and for each candidate x outputs a probability Pr (x).

(2) *The MaxEnt formula*

$$\Pr(x) = \frac{\exp(-\Sigma_i\, w_i \mathrm{f}_i(x))}{Z}\text{, where } Z = \Sigma_j\ \exp(-\Sigma_i\, w_i \mathrm{f}_i(x_j))$$

The formula says that to calculate this probability, one must do the things in Table 1 in order.

[2] Throughout this article, many of the tasks we perform with MaxEnt might also be performed with Noisy Harmonic Grammar (Pater 2016, Boersma and Pater 2016), but we find that at least with our own software MaxEnt gives more accurate results.

Table 1: The MaxEnt calculations for a given candidate x

Compute this	*Name of what is computed*	*How and why it is computed*
1. $\Sigma_i\, w_i \mathrm{f}_i\,(x)$	Harmony (Smolensky 1986)	Multiply x's violation counts for each constraint (designated $\mathbf{f}_i\,(\boldsymbol{x_j})$) by the weight of the constraint ($\boldsymbol{w_i}$), then add up the results across all constraints ($\boldsymbol{\Sigma_i}$). *All available evidence (i.e. constraint violations) bearing on a candidate is considered, in proportion to the constraint weights.*[3]
2. $\exp(-\Sigma_i\, w_i \mathrm{f}_i\,(x))$	eHarmony (Wilson 2014)[4]	Negate the harmony of x, then compute the function **exp( )** on the result, where $\exp(x)$ is a typographic convenience for e^x, $e \approx 2.72$. *In a series of candidates with ever greater harmony penalties, the probabilities descend not in linear fashion, but instead asymptote to zero (negative exponential curve) — certainty is evidentially expensive.*
3. $\Sigma_j \exp(-\Sigma_i\, w_i \mathrm{f}_i\,(x_j))$	Z, the "normalizing constant"	Compute the eHarmony of every candidate derived from the same input as x (x included), and sum these values.
4. $\dfrac{\exp(-\Sigma_i\, w_i \mathrm{f}_i\,(x))}{Z}$	Probability of x	Divide the eHarmony of x by Z (and similarly for all other candidates). *The probability of a candidate depends inversely on the probability of the candidates with which it competes (probability of all candidates must sum to one).*

In what follows, the most essential aspect of MaxEnt is that the constraint weights have a consistent and intuitive interpretation: the higher the weight, the lower the probability of candidates that violate it (for the exact relationship, see §8.4 below). In this context, the weight of a constraint is an appropriate measure of its role in determining the speaker's inventory of bigram outputs.

[3] This is not so for Optimality Theory, where decisions between candidates are made by the highest-ranking constraint that that distinguishes them, and all the evidence from other constraints is ignored.

[4] Wilson was joking in inventing this name (which also denotes a dating web site), but we feel it is quite helpful as a mnemonic.

4.2 Computing the weights and statistical testing

The other half of the MaxEnt approach is a method for fitting the constraint weights to match the data accurately, described for instance in Hayes and Wilson (2008:385-389). Uniquely among stochastic constraint-based frameworks, MaxEnt comes with a guarantee, in the form of mathematical proof, that appropriate searching can find the best-fitting weights. MaxEnt grammars also avoid false (artifactual) results delivered by other methods of data interpretation, as shown by Wilson and Obdeyn (2009) and the Appendix to this article. Another important aspect of MaxEnt is that it permits rigorous statistical testing of the hypotheses embodied in the constraints; for details, see §5.3 below.

5. Implementation

Although we are using MaxEnt in essence as a statistical method for detecting phonological effects, our implementation takes the form of a grammar and uses the normal GEN + EVAL architecture used in Optimality Theory.

5.1 Delimiting GEN

The GEN function provides the candidates across which our models will be distributing probabilities. What sort of GEN would be appropriate to our ends? The simplest approach would be to let GEN consist of all possible bigrams that can be formed from the words in the corpus. However, in practice this proves to be difficult: for Jane Austen, who used about 14,000 unique words in the works analyzed here, this would result in a candidate set of about 200 million items, making it computationally infeasible, at least with the resources we command.

However, it is possible to simplify the calculations. The key is to observe that the actual identity of the words in a bigram doesn't matter except insofar as their phonological properties lead to violations of the phonological bigram constraints we are testing. For example, all that is really relevant for us about the word *kiss* [kɪs] is that it ends with a sibilant (and so will form violations of *SIBILANT CLASH when the next word begins with a sibilant), that it bears final stress (and so will be involved in violations of *CLASH when the next word is initially stressed), that it begins with a [k] (and so will form violations of *GEMINATE when the preceding word ends in [k]); and so on. Because of this, it is feasible to pool the roughly 200 million bigram candidates into classes which are defined solely by those phonological characteristics that bear on the constraint inventory in (1). Under this approach, the tableaux will include frequency values, namely the number of actual bigrams in the corpus that fall into each pooled category. The resulting tableau is far smaller (38,016 candidates[5]), but the weights obtained from it are unchanged.[6]

[5] Here are the details: 2 penult stress levels × 2 final stress levels × 3 levels of sonority in the penult C × 22 possible final segments × 24 possible initial segments × 3 levels of peninitial sonority × 2 levels of initial stress. In the calculation of final and initial segments, we collapsed vowels to a single category. A sample spreadsheet for our data analysis may be viewed in the Supplemental Materials.

[6] A proof of this assertion can be obtained from the fact that standard search algorithms for MaxEnt weights upwardly follow the gradient on the hill of log likelihood, and that this gradient is equal to the value *Observed* −

In order to pool the candidates into classes, we adopt a set of what we will call CONSTRAINTS OF CONVENIENCE (Table 2) which embody the phonological properties of words that determine whether bigrams formed from them will violate the test constraints described earlier in §2.

Table 2*: Constraints of convenience*

Constraint	**Defined on**	**Used in assessing**
FINAL STRESS	Word 1	*CLASH
IAMBIC STRESS	Word 1	*IAMBIC CLASH
FINAL [−son][−son]	Word 1	*TRIPLE OBSTRUENT CLUSTER
FINAL CC	Word 1	*TRIPLE CONSONANT CLUSTER
FINAL VOWEL	Word 1	*HIATUS
{ FINAL C } (21 separate constraints; one for every final consonant)	Word 1	*SIBILANT CLASH, *GEMINATE, *BAD SONORITY, *TRIPLE OBSTRUENT CLUSTER, *TRIPLE CONSONANT CLUSTER, *NC̥
INITIAL STRESS	Word 2	*CLASH, *IAMBIC CLASH
INITIAL [−son][−son]	Word 2	*TRIPLE OBSTRUENT CLUSTER
INITIAL CC	Word 2	*TRIPLE CONSONANT CLUSTER
INITIAL VOWEL	Word 2	*HIATUS
{ INITIAL C } (23 separate constraints; one for every initial consonant)	Word 2	*SIBILANT CLASH, *GEMINATE, *BAD SONORITY, *TRIPLE OBSTRUENT CLUSTER, *TRIPLE CONSONANT CLUSTER, *NC̥

Once the constraints of convenience have received their proper weights in the MaxEnt analysis, they will form a baseline model of the phonological composition of the corpus, reflecting the phonological characteristics of the words available in the lexicon and the overall frequencies with which these words are used.

Here is an example of how our procedure would be applied to the Jane Austen corpus. The corpus includes the bigram *exact plan* [əgˌzækt ˈplæn], which falls under the scope of the constraints of convenience FINAL STRESS, IAMBIC STRESS, FINAL CC, FINAL [−son][−son], FINAL [t] (all for Word 1); and INITIAL STRESS, INITIAL CC, and INITIAL [p] (for Word2). *Exact plan* thus is part of bigram category that, it turns out, includes precisely two other members: *unjust praise* and *distrust providence*. We therefore install in our tableau the frequency value 3 for the abstract candidate class that includes these bigrams. We similarly classify all of the bigrams in the corpus, using custom software,[7] which outputs tableaux in the form of a spreadsheet. These tableaux have 38,016 rows of candidates, and there are 53 columns of violations (corresponding to the total number of constraints of convenience) for baseline modeling, plus 9 additional

Expected for the *pooled* violation counts of each constraint (see e.g. Hayes and Wilson 2008:388-389). A simple example illustrating the feasibility of our pooling procedure appears in the Supplemental Materials.

[7] A note on procedure: it has been our practice to write all software for the project in two independent versions, each author using a distinct programming language, and checking to make sure that our programs are yielding essentially identical results.

columns (per §2) when we are testing the effect of phonological constraints. A sample spreadsheet file may be viewed in the Supplemental Materials.

5.2 Finding the weights

There are many forms of software that can fit MaxEnt constraint weights to data. We used a custom program written by Tim Hunter,[8] which we favored for its speed. We checked the results from Hunter's program by running the same input files with the Solver utility in Excel (Fylstra et al. 1998), obtaining very similar results.

5.3 Assessing the results

Statistical testing for our results takes the form of model comparison (see, e.g., Wilson and Obdeyn 2009, Morley 2015, Shih 2017b): we compare the accuracy of two models, one including the phonological bigram constraints being tested, the other not. The key numerical value used for evaluation is the LIKELIHOOD a grammar assigns to the data; this is calculated by multiplying the probabilities assigned by (2) to every datum. Likelihood is then converted for computational convenience into log likelihood by taking the natural logarithm of the result. For purposes of statistical testing, two log likelihoods are computed: that of a baseline model that includes just the constraints of convenience, and that of a full model that also incorporates our phonological constraints. We then use the Likelihood Ratio Test (Wasserman 2004:164) to determine whether the phonological constraints significantly improve the accuracy of the model.[9]

5.4 Corpora employed

We examined fourteen corpora. Eight represent authors from the 19th century canon; such authors are beyond any doubt competent native speakers, and their works are out of copyright and available in abundance in carefully prepared electronic editions (we used texts from Project Gutenberg, www.gutenberg.org). The remaining corpora are of spoken language, gathered from various sources, either public or available by subscription. For one of the spoken corpora, we amalgamated five similar sources to obtain a total similar in length to the other corpora.[10]

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[8] https://github.com/timhunter/loglin.

[9] Our procedure for pooling individual words into categories based on their phonological properties (§5.1) evidently does not affect significance values. In the schematic simulation described there (and in the Supplemental Materials), the log likelihood values obtained using word-by-word data differ from those obtained from pooled data (less detail is available for matching the frequencies), but for the phonological constraints being tested, weights and significance values come out the same.

[10] A note on procedure: five of the corpora (Austen, Darwin, Five-Spoken, Twain, Hawthorne) were available to us as we worked out our software and methods; the nine others were examined after the software and analytic methods had been finalized.

Table 3: Corpora examined

Text	*Approx. Length in words*	*Source*
Written texts:		
Six novels by Jane Austen	722,000	Project Gutenberg
Six non-fiction works by Charles Darwin	935,000	Project Gutenberg
Six novels by Charles Dickens	709,000	Project Gutenberg
Six novels by Nathaniel Hawthorne	592,000	Project Gutenberg
Nine novels by Jack London	739,000	Project Gutenberg
Six works by Herman Melville	786,000	Project Gutenberg
Four novels by Anthony Trollope	756,000	Project Gutenberg
Six novels by Mark Twain	568,000	Project Gutenberg
Spoken texts:		
Committee corpus: transcripts of committee hearings from the Corpus of Spoken Professional American English	878,000	www.athel.com/cpsa.html
Fresh Air corpus: transcripts of the "Fresh Air" program on National Public Radio	724,000	www.npr.org/programs/fresh-air/archive, interview transcriptions from 5/15/2018 to 9/12/2018
Michigan lecture: the lecture portions of the Michigan Corpus of Academic English	912,000	www.lib.umich.edu/database/link/11887
Michigan nonlecture: the remaining portions of the Michigan Corpus of Academic English	709,000	www.lib.umich.edu/database/link/11887
Spoken set, a merged set of several spoken corpora, containing: British Academic Spoken English Corpus Beatles Interview Corpus (Stanton 2016) Buckeye Corpus HCRC Map Task Corpus 2016 Primary Debates Corpus	969,000	 www.warwick.ac.uk/fac/soc/al/research/collections/base/history nyu.app.box.com/s/ku8b32q1orh6twkoank40l3zjc146yog buckeyecorpus.osu.edu/ groups.inf.ed.ac.uk/maptask/maptasknxt.html www.kaggle.com/kinguistics/2016-us-presidential-primary-debates/home
White House corpus: Collected transcripts of live questions and answers from White House press briefings (1994-1997)	758,000	www.athel.com/cpsa.html

5.4 Editing the bigram sets

Using software, we isolated the words of each corpus and converted them to phonetic transcription, relying on an augmented version of the dictionary used in Hayes (2012),[11] itself an

[11] Accessible at linguistics.ucla.edu/people/hayes/BLICK/.

edited version of the CMU Pronouncing Dictionary (www.speech.cs.cmu.edu/cgi-bin/cmudict). In order to limit the number of bigrams that could not be analyzed because we lacked a dictionary for one of their members, we augmented our dictionary to include all words that had a frequency greater than 100 in any of the corpora; we also auto-created inflected forms (plural, past, gerund) of the entries. In the end, our efforts provided phonetic transcriptions for 72.8% of the types and 96.9% of the tokens in the corpora. This implies that the probability that a bigram would go unanalyzed because we lack a dictionary entry for one of its words is about 0.06. One further edit was performed: we removed all bigrams from our bigram sets that began with an allomorph of the indefinite article *a*/*an*. Our purpose was to avoid artificial inflation of the weight of *HIATUS, which would have resulted from including them.

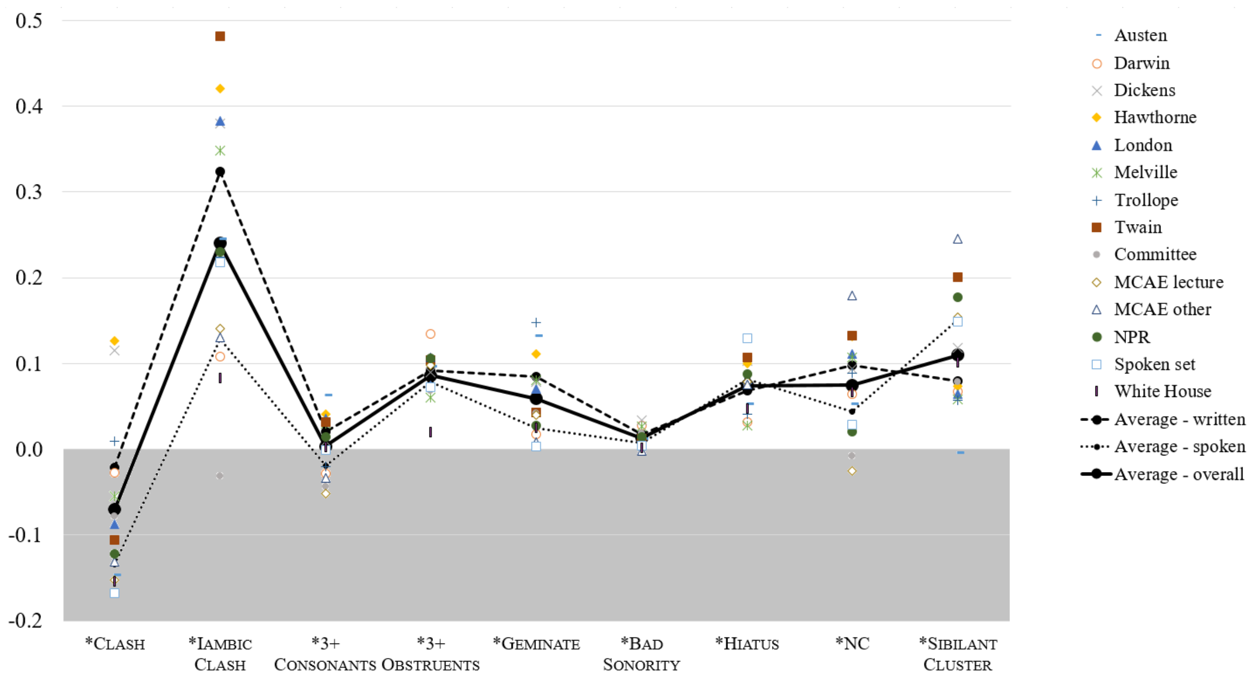
Each corpus was analyzed in several versions, edited to include different subsets of the full bigram set. Our purpose, discussed in detail below, was to test for the effects of syntactic variation, fixed phrases, and lexical frequency. We will first report on the most heavily edited versions of the corpora, which were shortened in three ways. First, for reasons discussed in §7.2, we discarded bigrams that were separated by a major prosodic break, as diagnosed by the presence of punctuation. Second, for reasons discussed in §8.1, we reduced the text to its HAPAX bigrams; that is, those that occurred only once. Lastly, for reasons discussed in §8.2, we discarded bigrams that contained function words. We will call the form of analysis that employs such bigram sets the Core condition. It emerged from our study that the Core condition was the most stringent test for the existence of phonological effects, so we report it first.

6. Findings for the Core condition

In every corpus, the addition of phonological constraints to the model made a strong positive difference to the model's accuracy. The improvement in the log likelihood of the model ranged from 18.3 for the Committee corpus to 127.6 for the Hawthorne corpus. A likelihood ratio test for the degree of improvement created by adding in the phonological constraints (9 degrees of freedom) yielded significance values ranging from $p = 0.00003$ for the Committee corpus (worst case) to $p = 7.6 \times 10^{-50}$ for the Hawthorne corpus. The full set of significance results may be viewed in the Supplemental Materials.

The improvement in model accuracy is the work of most, but not always all, of the constraints we tested. Figure 2 shows the weight of each of the constraints as fitted to the Core corpora; we include boldface lines connecting average values for all corpora, as well as dotted lines for all of the written corpora and all of the spoken corpora.

Figure 2: Weights obtained for 9 phonological bigram constraints, Core condition.



Plainly, there is variation from constraint to constraint, with frequent negative weights for *CLASH — implying it is better to have a stress clash than not. In §8.2 below we offer an explanation of this aberration, suggesting that speakers actually do respect *CLASH when they construct sentences, and that the negative weights observed here are an artifact of the Core condition's bigram exclusion criterion.

In general, the written corpora have higher weights than the spoken ones, plausibly the result of the opportunity writers have to ponder the phonological well-formedness of what they are writing and improve it with edits.[12] Nevertheless, even the spoken corpora show massive statistical effects of phonological markedness. We return to the issue of spoken vs. written language in §8.6.[13]

7. Control studies

Our statistically significant results, found in the stringently-edited Core condition, are encouraging, but invite further scrutiny. In this section, we offer two further tests of our general hypothesis that phonological constraints influence sentence formation across the board.

[12] For discussion of evidence that writing is genuinely a phonological process, see Schlüter (2005:50-55) and Shih and Zuraw (2017:e320-e321).

[13] Beyond the written/spoken difference, there is considerable residual variation among the individual corpora, a pattern that repeats itself for all the analyses and for which we have no explanation.

7.1 Pseudoconstraints

For the first test, we invented an alternative constraint set which was intended (unlike the set in §2) to be utterly arbitrary, so we call them “pseudoconstraints.” To the extent that the pseudo-constraints reflect general principles of markedness at all, one would expect that they would be violated *more* frequently than at random, not less, in our bigram samples. Our checking with the UCLA Phonotactic Learner indicated that our pseudo-constraints play essentially no role in regulating the sequencing of sounds within words.[14]

The set of pseudo-constraints is as given in (3).

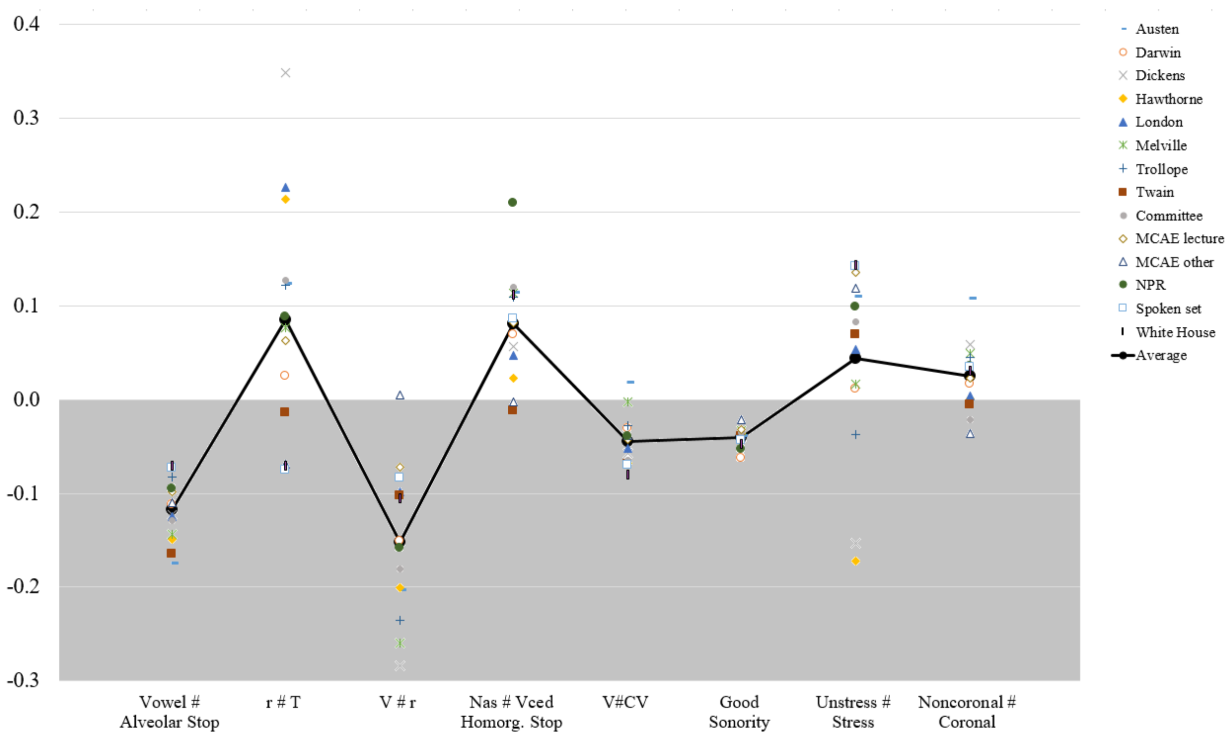
(3) *List of “pseudo-constraints” tested*

	Pseudo-constraint	*Description*
a.	Vowel # Alveolar stop	Open syllable, unmarked consonant
b.	r # Alveolar stop	
c.	Vowel # r	
d.	Nasal # Voiced homorganic stop	Obeys postnasal voicing tendency
e.	V # CV	Maximally unmarked syllabification
f.	In C1 # C2, C1 has more sonority than C2	Obeys the Syllable Contact Law
g.	Unstressed syllable # Stressed syllable	Highly frequent non-clashing configuration
h.	Noncoronal C # Coronal C	See Blust (1979), arguing that this is the unmarked order.

Applying the same test as in §6, we observe a very different outcome: the eight pseudo-constraints have near-zero weights, suggesting essentially random variation.

[14] In particular, constraint (3h) receives the small weight of 0.25; the others zero.

Figure 3: Weights obtained for 8 pseudo-constraints



In other words, it appears that it is the fact that our real constraints ban *marked* configurations that gives them their generally positive weights.

7.2 Violations across phrasal breaks

The second test for the validity of our results is based on the widely observed pattern that processes of phrasal phonology are blocked across prosodic breaks; see, e.g., Nespor and Vogel (1986/2007), Hayes (1989). To give just one of many empirical examples, Jun (1996:70) demonstrates that the phonological process of Intervocalic Lenis Stop Voicing in Korean is blocked across Accentual Phrase breaks. Thus, in (4), underlying /k/ is converted to [g] when the intervocalic environment is created within an Accentual Phrase, but intervocalic /p/ remains voiceless, since the intervocalic environment arises across a phrase break.

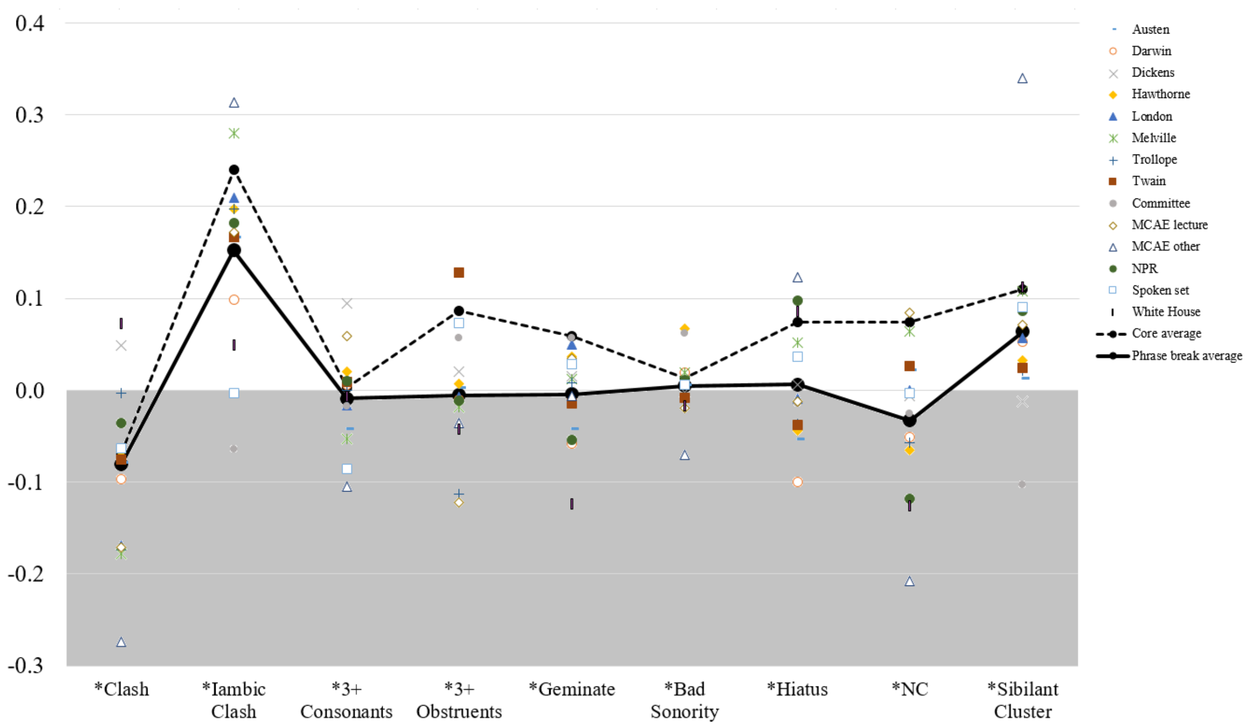
(4) *Korean Intervocalic Lenis Stop Voicing blocked by Accentual Phrase break*

/ (kəmɨn kojaŋi-e)$_A$	(palmok)$_A$ /		phonemic form with Accentual Phrasing
[g]	[p]		phonetic output
black cat-GEN	ankle		gloss: ‘the ankle of the black cat’

This is stated in process terms, but is more appropriately treated for present purposes with constraints: there is a Markedness ban on voiceless intervocalic plain stops that dominates Faithfulness for voicing, but is defined to be applicable only within Accentual Phrases. We expect that similar phrase-bounding is likely to hold true for the markedness constraints for English examined here.

This forms the basis for the test we next describe. In our Core condition (§6), we deliberately excluded bigrams whose words are separated by punctuation, which is generally diagnostic of a phrase break. Here, in a contrasting Phrase Break condition, we do the opposite, retaining bigrams *only* when they are formed across punctuation. The graph in Figure 4 shows the weights of the constraints in the Phrase Break condition; the boldface line represents the average across corpora, and the dotted line shows the comparable averaged results for the Core condition.

Figure 4: Weights obtained for 9 phonological bigram constraints, Phrase Break condition.



As can be seen, the weights for the phrasal-break data are scattered about zero, meaning that the effects mostly disappear across phrase breaks — following the normal typology of Markedness constraints. This difference would hardly be expected if the original effect were just a random occurrence, but it makes perfect sense if what we have found is a true phonological effect.

8. Seeking the causes

Our tentative conclusion, then, is that across-the-board phonological markedness effects do indeed obtain in sentence formation. In particular, the effects occur only for constraints that are phonologically plausible (§7.1), and they largely evaporate across phrase breaks, as one would expect in phrasal phonology (§7.2). We next explore versions of our corpora that are edited in other ways, with the goal of learning something about the mechanisms responsible for these markedness effects. We relate our findings to the research literature reviewed in §1.

8.1 Varying bigram frequency to test listed phrases

We first attempt to find in our own data a pattern discovered for compound words by Martin (2011). Using a different statistical technique (see Appendix), Martin found substantial underrepresentation of markedness violations in bigrams consisting of the component elements of compound words. In Navajo, he detected underrepresentation of compounds violating Sibilant Harmony, an important principle of Navajo phonology. In English compounds, as already noted, he found that geminates are disfavored. For Martin, the explanation of these patterns lies in the process whereby newly created compounds propagate through a speech community and become accepted into the lexicon as listed items. Specifically, he suggests that phonotactic markedness is a barrier to such acceptance. Mollin (2012) has found similar evidence that binomials (*X and Y*) are less likely to lexicalize to a fixed order when they violate phonological constraints.

While our own corpora are not limited to compounds, there is nevertheless reason to think that the concept of preferential lexicalization of phonologically-optimal sequences might be applicable to our own data. This is because a separate research tradition has found evidence that phrases are also frequently lexicalized; see e.g. Pauley and Snyder (1983) and Jackendoff (1997:§7.2). Indeed, a widely expressed view is that the number of memorized phrases in a language is very large, perhaps even greater than the number of memorized words (Mel'čuk 1998).

One other key research result is that lexicalization is dependent on frequency: the more frequent a word sequence is, the more likely it is that it will be lexicalized. This has been established in experimental work; see instance Arnon and Snider (2010) and the body of work cited there. As an intuitive illustration, we list below some word bigrams that appear frequently in the Austen corpus:

(5) *Some familiar-sounding bigrams from the Austen corpus*

a. *Content words*

very well, great deal, young man, very good, few minutes, young ladies, next morning, soon afterwards, same time, young woman, next day, soon after, very soon, only one, last night

b. *With function words*

and then, my dear, the next, I think, I believe, at home, at first, at once, in love, in town, going to, it is, do not, did not, was not[15]

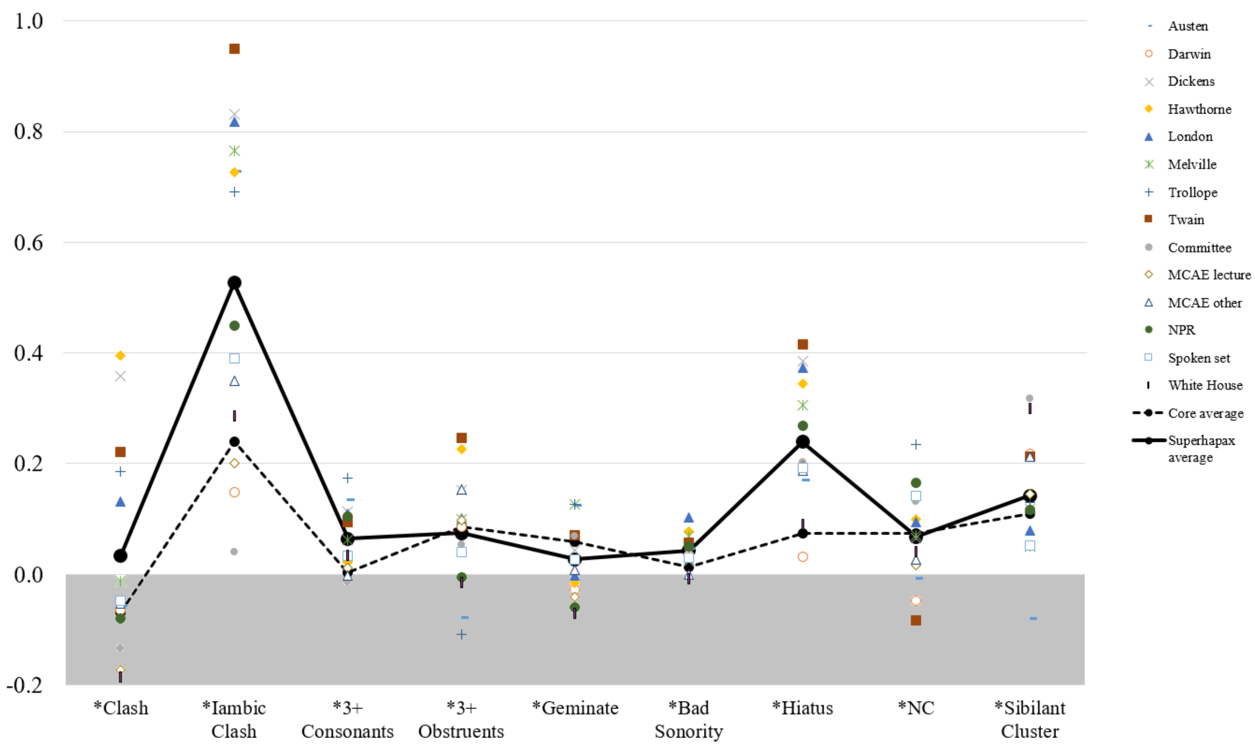
Putting all these elements together, we hypothesize that the Martinian mechanism enforcing phonological unmarkedness in compounds would be expected also to apply to phrasal sequences. Since lexicalized bigrams tend to be frequent, it should be the case that when we look at frequent bigrams, we will find an enhancement of phonological markedness effects.

[15] Observe that the last five items have contracted forms.

To this end we set up a Superhapax condition, in which the corpora were edited to include only the bigrams of frequency 2 or greater. These edited corpora otherwise matched the criteria for the Core condition above: they excluded function word bigrams and bigrams formed across punctuated phrasal breaks.

Our findings for the Superhapax condition are given in Figure 5, which gives the weights obtained for all 9 phonological constraints across 14 corpora; the boldface line represents the constraint weights averaged across corpora, and the dotted line shows the comparable value for the earlier Core condition.

Figure 5: Constraint weights for 14 corpora, Superhapax condition (phrase-internal, function words excluded, superhapax bigrams)



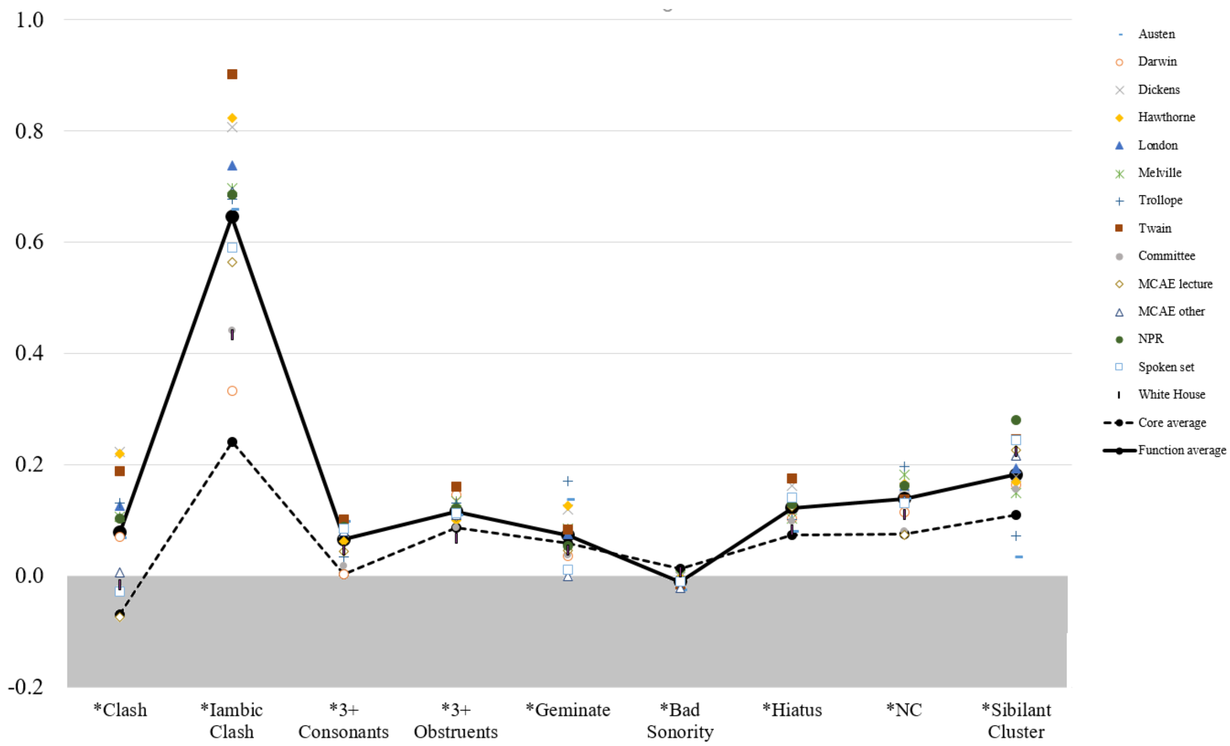
It should be clear from the figure that the superhapax bigrams generally yield stronger phonological markedness effects than the hapax bigrams. We draw the inference that listed phrases tend to be less phonologically marked, and that the responsible mechanism is plausibly what was outlined above, i.e. that the Martinian principle of preferential lexicalization for phonological unmarked forms carries over to lexically listed phrases.

8.2 Function words and syntax

The data described in this section consist of another variant of our bigram sets, again created for each of the 14 text corpora. Here, we diverge from Core in a different way: we include the bigrams that contain function words (e.g. determiners, prepositions, pronouns, auxiliary verbs, complementizers, stressless adverbs). We retain from Core the practice of keeping only hapax bigrams, as we are not interested here in the effects of listed bigrams (such as (5b)) that contain function words. We also retain from Core the restriction that the bigrams must be contained within phrases, as diagnosed by punctuation. We will refer to this as the Function condition.

Like the Superhapax condition, the Function condition yields higher weights than Core for the phonological markedness constraints, as Figure 6 shows.

Figure 6: Constraint weights for 14 data corpora, Function condition (phrase-internal, function words included, hapax bigrams)



We think the factor most likely to be responsible for this effect is syntax. As already noted, the research literature (§1) has adduced multiple instances showing that when the syntax offers a binary choice for expressing the same meaning, speakers tend to pick the phonologically less marked option; recall the examples of Tagalog *Adjective + linker + Noun* vs. *Noun + linker + Adjective*, English *give X to Y* vs. *give Y X*, and English *Y's X* vs. *X of Y*. Typically, at least one of the choices employs a function word. We consider here a taxonomy of possibilities, based on where the function word occurs.

In the first case, *both* syntactic variants include a function word. For instance, in the Tagalog case, the linker morpheme *na* appears in either word order. As Shih and Zuraw (2017) note, if one flanking word ends in a nasal and the other does not, then one of the two orders will incur a violation of NASAL OCP; an example is *áma<u>ng n</u>a túnay* vs. *túnay na ámang* ('real elder/father', p. e326). We expect, given Shih and Zuraw's findings, that Tagalog speakers in forming sentences will particularly favor unmarkedness in this syntactic context, since the grammar gives them a ready opportunity to do so. Consider, then, how such a case would be treated when examined under our Core condition: all of the examples of this syntactic construction would get culled out, because the relevant bigrams contain a function word (*na*). The upshot is that the weight of the markedness constraint NASAL OCP will go *down* in Core condition relative to the Function condition, since some of the best evidence for it has been discarded.

The second syntax-related pattern occurs where a function word appears in only one of the two syntactic options, namely the one that is phonologically less marked. The canonical instance of this is *CLASH. For instance, if the two syntactic variants are the two forms of the dative construction (*gíve bóoks to Bíll*, *gíve Bíll bóoks*) then the dative function word *to*, being stressless, will often avert a clash (here, the clash between *Bíll* and *bóoks*). If, as Shih (2017a) suggests, variants of the dative construction are indeed deployed to reduce phonological markedness, then the procedure used in forming the Core corpora will create a strong distortion, because the discarded bigrams are clash-free, whereas the retained ones are clashing. The same outcome will occur for other syntactic constructions — see Shih (2017a) on genitives, Wasow et al. (2015) on *to*-dropping, and Jaeger (2006) on *that*-dropping — and thus is probably responsible for the anomaly observed in §6, namely overrepresentation in many corpora under the Core condition of *CLASH violations.[16]

In principle, there should be a third case, one in which the appearance of function words consistently induces, rather than averts, violations of a phonological constraint. In such a case one would expect higher constraint weights in the Core than in the Function condition. We have alerted ourselves to detect such cases empirically but have not yet found any.[17]

In sum, when compared with the Function condition, the Core condition emerges as informative precisely for its distortions, which involve syntax. When we remove function words, we remove many of the examples where syntactic choices permit speakers to avoid phonological markedness, reducing the constraint weights. When the removal actually *targets* the unmarked cases, we sometimes get negative weights in Core even for markedness constraints which have strong support elsewhere in the language. The result is to provide indirect evidence to support what other scholars have shown directly through scrutiny of particular constructions. Our own comparisons demonstrate how strong the effect of syntactic choice is likely to be, and how it applies for multiple constraints.

8.3 Rethinking the results for the Core condition

We return to the fact that although the constraint weights found in the Core condition were generally smaller, they were nonetheless generally positive and consistently statistically significant in the aggregate. Conceivably, these findings represent residual effects of listed phrases and of syntax that proved impossible to control for completely using our methods; e.g. perhaps some of our hapax bigrams really were listed phrases that by accident happened to be used just once in the corpus; or there are major effects of syntactic choice that involve no

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[16] By the same token *IAMBIC CLASH might also be expected to be overrepresented in the Core-condition modeling, something that only happened for the Committee corpus. We suggest that this constraint is so powerful That its effects will be found even under the deliberately-insensitive Core method.

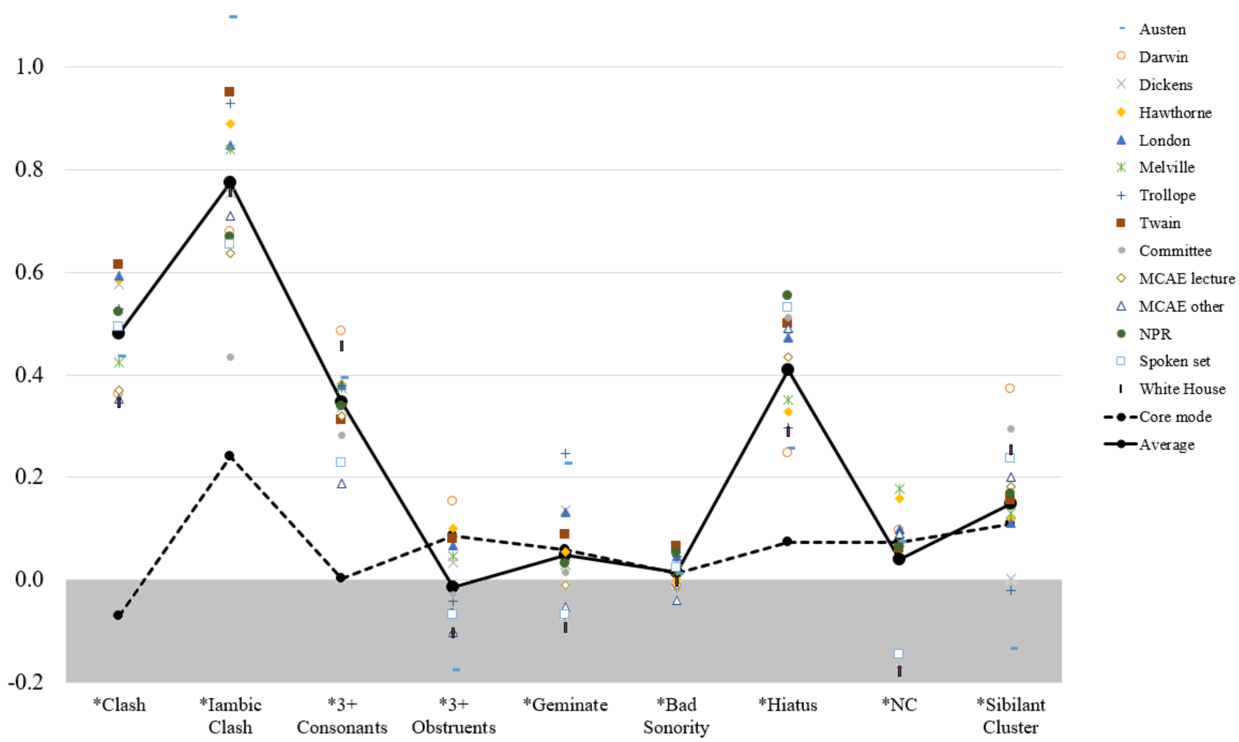
[17] A sensible place to look is *LAPSE, which however would require us to expand our search method to an infeasible number of candidates.

function words. The effects seen in the Core condition may also reflect word choice, as documented by Schlüter and colleagues (§1).

8.4 Including all factors together

Lastly, in Figure 7 below, we give our findings for a set of minimally-curated bigrams, which folds together hapax and the superhapax bigrams, includes function words, and counts tokens rather than types, so that a bigram that appears *n* times is counted *n* times rather than just once. The only bigrams that are excluded from Figure 7 are those occurring across prosodic breaks. Since this condition is not curated in any way (other than the well-motivated phrase break exclusion) we call it the Simple condition.

Figure 7: Constraint weights for 14 data corpora, Simple condition (hapaxes and superhapaxes together, counted by tokens, function words included, phrase-internal only)



As might be expected, the effects here are at their strongest. This is because we have both included superhapax bigrams (where lexical listing encourages obedience to markedness constraints), and function word bigrams (which incorporate the reduced markedness resulting from syntactic choices). The combination also introduces an additional set of lexically-listed bigrams that were absent from the Superhapax condition, namely those that include function words. Lastly, using token counts instead of types would also be expected to increase the effect of phonological markedness, since the highest-frequency bigrams, which are most likely to be listed, receive more influence when token-counting is employed.[18]

A quirk seen in Figure 7 is that *3+ CONSONANTS rises in weight and *3+ OBSTRUENTS falls, relative to the Core, Superhapax, and Function conditions. These two constraints are "ganged" (Jäger and Rosenbach 2008), in the sense that whatever violates *3+ OBSTRUENTS also violates *3+ CONSONANTS; so that a triple obstruent cluster automatically accrues whatever penalty falls on triple consonant clusters. What this implies is that triple obstruent clusters are avoided in the Simple condition, but not any more than any triple consonant clusters are. We observe also that *IAMBIC CLASH is ganged with *CLASH, so that the harmony penalty incurred by any iambic clash is in fact the sum of the weights of *CLASH and *IAMBIC CLASH.

8.5 Interpreting the constraint weights

What do the constraint weights of Figure 7 mean in terms of actual probability of use? The MaxEnt formula (2) provides a concrete answer. Imagine two candidates, identical except that one violates a constraint with weight *w* and the other does not. It is readily deduced from (2) that the probabilities assigned to them will occur in a particular RATIO (odds): the probability of the non-violator is e^w times higher than the probability of the violator.

(6) *Probability ratio of Candidate 1 and Candidate 2, differing in only one constraint violation*

$$\frac{\text{P(Candidate 1)}}{\text{P(Candidate 2)}} = \frac{\frac{e^{-H}}{Z}}{\frac{e^{-(H+w)}}{Z}} = \frac{e^{-H}}{e^{-(H+w)}} = \frac{1}{e^{-w}} = e^{w}$$

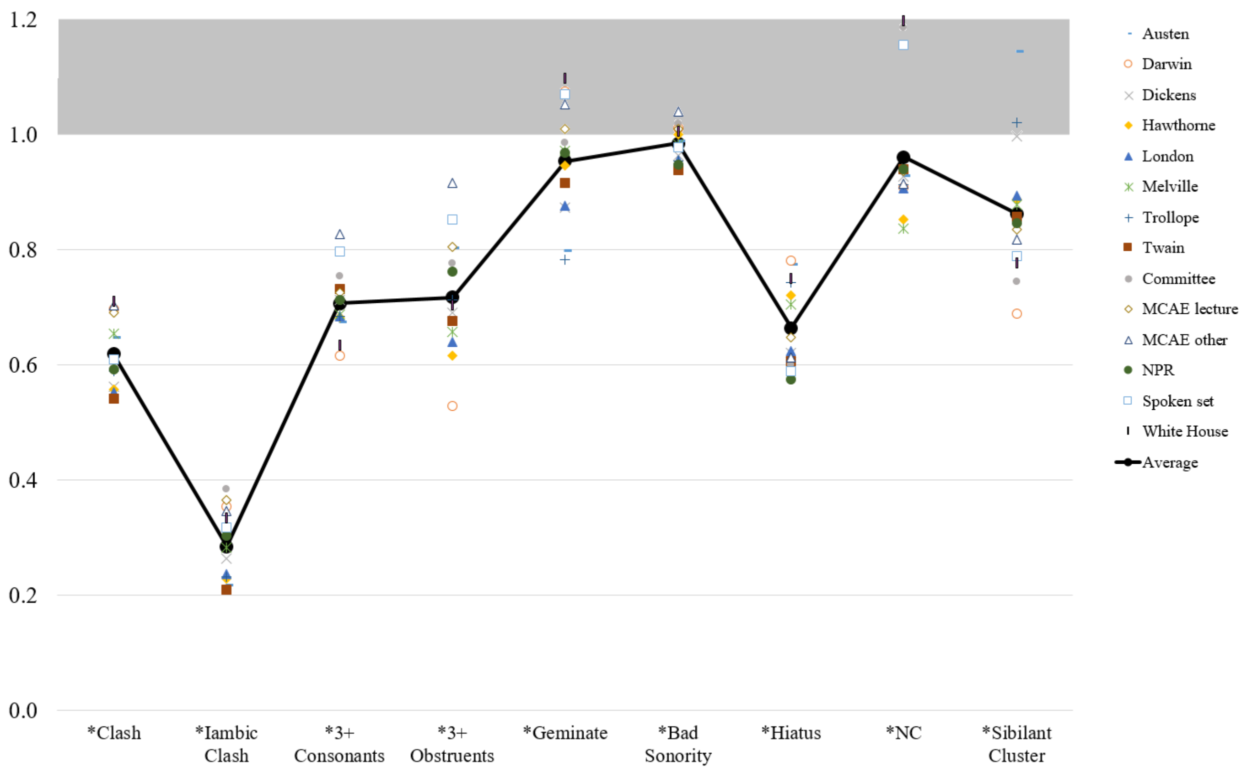
where

H = harmony penalty resulting from shared violations
w = penalty for violating constraint C

We use this formula to replot the data of Figure 7 to display these probability ratios. We have also augmented the weights of *IAMBIC CLASH and *3+ OBSTRUENTS with the more general constraints (*CLASH and *3+ CONSONANTS) that gang with them; this gives a clearer picture of their empirical effect. The result is shown in Figure 8.

[18] We checked the specific contribution of token frequency by creating a further condition just like the Superhapax condition, except that it counted by tokens instead of types. A substantial increase in average constraint weight resulted, namely types 0.135, tokens: 0.186.

Figure 8: Data of Figure 7 replotted as probability ratios; ganging applied to two constraints

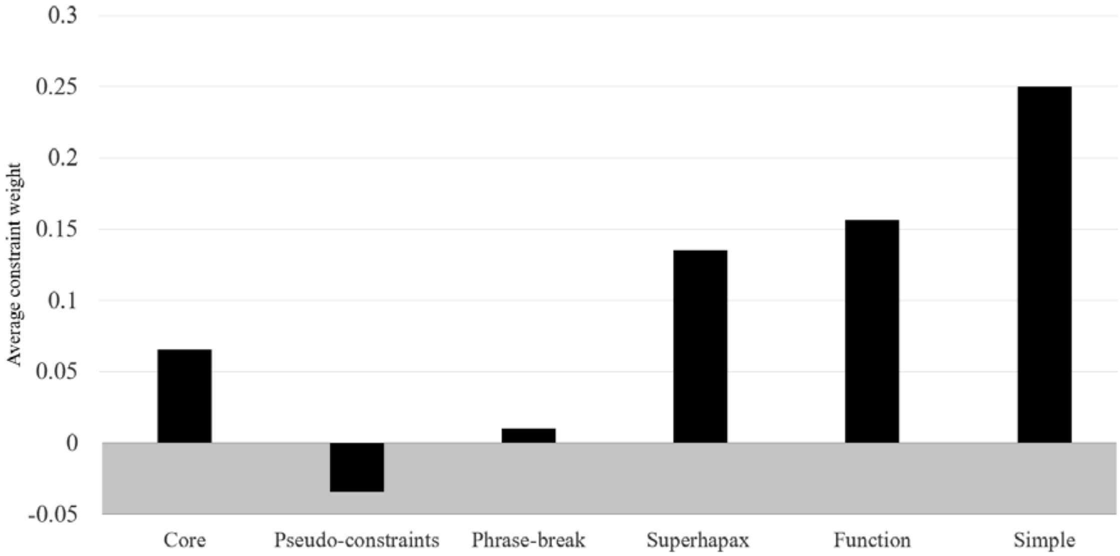


As can be seen, the average reduction in probability (one minus the value shown) ranges from the remarkable 71.5% for *IAMBIC CLASH to just 1.5% for *BAD SONORITY.

8.6 Overall summary and statistical testing

As an overview of our findings, Figure 9 gives the average constraint weight for all six conditions.

Figure 9: Average constraint weights for each condition



The first column, representing our Core condition (§5), shows a relatively weak effect of phonological markedness, but one that nevertheless emerges as highly statistically significant (taking the constraints in the aggregate) in every one of our 14 corpora, including the spoken ones. The next two columns show that the phonological effects largely disappear under the two control conditions we examined (§7): the substitution of pseudo-constraints for true markedness constraints, and the inspection of bigrams formed across phrasal breaks, where phonological constraints are mostly inapplicable. The next two columns demonstrate that the phonological effects are stronger in listed bigrams (Superhapax condition, §8.1), and that the characteristic ordering of function and content words by the syntax creates the opportunity for speakers to favor phonologically unmarked bigrams (Function condition, §8.2). The final, tallest column (Simple condition, §8.4) illustrates the combination of these effects, augmented by the effect of token frequency.

We can also obtain an overview of the strength of the individual constraints, using the results for the Simple condition to test significance, using the likelihood ratio test with 1 degree of freedom. The nine constraints we originally chose for testing emerged with quite different outcomes, as seen in Table 4.

Table 4: Results of likelihood ratio test for nine constraints, Simple condition

Constraint	Change in log likelihood when included in model: average across corpora	*p*
*CLASH	2840.2	< 0.0001
*IAMBIC CLASH	783.2	< 0.0001
*3+ CONSONANTS	1063.9	< 0.0001
*3+ OBSTRUENTS	−3.5	< 0.01 (wrong direction)
*GEMINATE	43.8	< 0.0001
*BAD SONORITY	33.3	< 0.0001
*HIATUS	1633.3	< 0.0001
*NÇ̥	−1.5	n.s.
*SIBILANT CLUSTER	76.7	< 0.0001

For most constraints, the average effect across corpora in the Simple condition is substantial and corresponds to a very low *p*-value. The exceptions are *3+ OBSTRUENTS, which the reader will recall, is ganged with *3+ CONSONANTS, so that what the results mean is simply that the status of the members of a long cluster does not matter at this level.[19] For *NÇ̥, it should be recalled that our original basis for including the constraint in our analysis was its typological pedigree; it is not valid as a word-internal constraint for English. This bears on the question of the mechanism behind these effects, which we turn to below.

For full reporting of all significance values (by corpus, condition, and constraint), see Supplemental Materials.

Lastly, we return to the difference between written and spoken corpora, already observed in the Core condition. As Table 5 shows, this difference persists in the other test conditions.

Table 5: Average constraint weights for written vs. spoken corpora, all test conditions

	Core	*Function*	*Superhapax*	*Simple*
Written	0.084	0.174	0.176	0.277
Spoken	0.040	0.133	0.082	0.213

[19] In our word internal checking (see section §2), the weight of *3+ OBSTRUENTS, ganged with *3+ CONSONANTS, is modest (*3+ OBSTRUENTS 1.33, *3+ CONSONANTS 1.94).

9. General discussion

At this point we have demonstrated, we believe, that our bigram/MaxEnt method diagnoses widespread avoidance of phonological Markedness violations in English, and that the mechanisms whereby this happens include syntactic choice, a Martinian tendency to preferentially list phrases that are phonologically unmarked, and probably also lexical choice. We next consider various interpretations and implications of our findings.

9.1 The hypothesis of raw phonetic difficulty

Before making grander claims, we should consider a very modest explanation of our findings. Under this view, the effects we are seeing are not even grammar. Work in phonetically-based phonology (e.g. Hayes 1999, Steriade 2001, Hayes et al. 2004, Wilson 2006) suggests that phonological constraints might be construed as devices that arise as grammatical responses to phonetic difficulty. In this view, stress clashes, adjacent sibilants, and the like are difficult for *all* human speakers, but their distribution in particular languages are regulated by the constraints of the phonological grammar. The idea would be that the effects we are seeing result not from grammar but from phonetic difficulty itself, the essential linking hypothesis being that in every language it is a pragmatic principle of speaking (or writing) to avoid such difficulties to some degree.

However, a crucial finding of Hammond's (2016) work on the Rhythm Rule suggests this hypothesis is untenable. Hammond not only finds (as we and others did) that iambic clashes are statistically avoided in English, but such clashes are avoided even when repaired: a phrase like *ùnkind pérson*, derived from /*unkínd* + *pérson*/, has no clash, but it is still partially avoided. The natural interpretation of this under our assumptions is that what is being avoided is a *Faithfulness* violation, namely of whatever Faithfulness constraint is violated in shifting the underlying stress of *unkínd*. The hypothesis of raw phonetic difficulty cannot explain Hammond's result.[20] Moreover, to the extent that avoidances are language-specific (see Shih and Zuraw 2017 and below), we likewise cannot accept the raw phonetic difficulty theory as valid.

9.2 Architecture of the language faculty

Assuming, then, that the effects we observe are the consequence of grammar, we turn to the question of what sorts of grammatical architecture could explain our findings (and more generally, those of all researchers who have critically addressed the feed-forward model; §1).

A suggestion made repeatedly in the research literature is that although grammatical architecture should recognize distinct forms of representation (syntactic, semantic, phonological, etc.), it should engage with these representations in parallel rather than serially; see Sadock (1991), Jackendoff (1997, 2002, 2010), Bresnan (2000), Anttila (2016), and Shih and Zuraw (2018). The key idea is that it is possible to maintain distinct types of representations, each

[20] For other constraints we studied, violations are also sometimes repaired in the phrasal phonology; e.g. clusters are simplified through consonant drop, and hiatus resolved by [ʔ] insertion. We have no way of assessing when such repairs are taking place (thus incurring Faithfulness violations) and we record them simply as Markedness violations; the essential point is that either way there is a cost in harmony.

governed by appropriate constraints, without demarcating separate components among which the direction of information flow is stipulated. Bresnan (1998:67) describes this general approach as follows, referring to “a class of frameworks in which the [grammar] of language is modeled as linked parallel structures, each of a different formal character. The grammar consists of a set of local co-descriptive constraints on partial structures. There are no derivational or transformational operations involved: grammatical structures are defined by constraint satisfaction. Each of the parallel structures of [such theories] models a different dimension of the structure of language.”

We propose that this general view of grammatical architecture is correct, and further that it should be implemented in MaxEnt. Parallelist studies involving syntax and phonology have already been pursued within a MaxEnt framework, notably in studies such as Bresnan et al. (2007), Shih et al. (2015), and Shih and Zuraw (2017).

Why is the combination of parallelist architecture and MaxEnt appealing from the viewpoint of our data? The key point is that we found effects essentially across the board; all constraints that are valid word-internally were observed to have at least some effect on sentence formation. If this generalization holds, we should be seeking a model in which it falls out more or less automatically.

The result follows from the MaxEnt math (2), which tells us that while constraints can have their empirical effects greatly weakened by conflicting constraints, *they can never be entirely turned off*. This means that we are likely to find *some* sort of effect for any phonological constraint in the grammar, provided our method of observation is sufficiently sensitive. We think that this is more or less what we have been seeing.

9.3 Restrictiveness

Zwicky and Pullum (1986) long ago argued for a pure feed-forward model on grounds of restrictiveness: the feed-forward architecture automatically rules out bizarre patterns like “a movement transformation that obligatorily moves ... [a] constituent that begins phonetically with a bilabial consonant” (p. 75). We agree with Shih and Zuraw (2018:4) that the right explanation for such absence is not feed-forward architecture but rather the distinct character of syntactic and phonological constraints (§9.2). Assuming that there exists syntactic movement into (for instance) Spec-CP, we assert it unlikely that the phonology would ever have a constraint specifically penalizing the absence of labials in Spec-CP. The empirical effects seen so far, both here and in the literature cited in §1, are compatible with the mechanism we propose, namely candidate competition regulated by competing syntactic and phonological constraints.

9.4 Choice of phonological frameworks

Rule-based phonology (Chomsky and Halle 1968), which still has many adherents, rejects a key idea of Optimality Theory and other constraint-based theories, namely, to do linguistics with the simplest possible ingredients. For phonology, the rules are dissolved and replaced with the formally simpler constraints. We can sometimes even identify the dissolution: a schematic phonological rule like A → B / C__D is reanalyzed as the Markedness constraint *CAD, ranked above the Faithfulness constraints that militate against A ~ B alternation. This "atomization" of the elements of the theory strikes us as sound scientific practice *a priori*, but of course empirically we want to know whether the atomized entities have an independent role to play, rather than being just notational variants for rule environments.

In this regard, our results add to the evidence that constraints do indeed have independent status, a conclusion already supported by the existence of conspiracies (Kisseberth 1970 et seq.), phonotactics (Kenstowicz and Kisseberth 1977), optionality patterns (e.g. Anttila 1997), and speech errors (Goldrick and Daland 2009). Our own findings do not concern phonological alternations (the focus of rules), but probability distributions in output forms generated by principles found throughout the entire grammar. Rule-based phonology has nothing to say about such cases, but they are a natural consequence of including phonological constraints in a parallelist MaxEnt system.

10. For future work

10.1 A puzzle from Hungarian

We sought to generalize our results by examining the phrasal patterning of three languages well known for their vowel harmony: Turkish (e.g., Clements and Sezer 1982), Finnish (Kiparsky 1973), and Hungarian (Siptár and Törkenczy 2000). Our tentative results indicate that both Turkish and Finnish texts show a modest tendency to avoid phrasal bigrams that violate their respective vowel harmony principles (backness harmony and rounding harmony for Turkish; just backness harmony for Finnish). However, bafflingly (from the viewpoint of our research experience), in Hungarian there is a statistically significant tendency to favor bigrams that actually *violate* the backness harmony found in the word-level phonology of language.

The Hungarian pattern finds least a modest rationalization in the principle, dating from Trubetzkoy (1939), that phonology provides *Grenzsignale*, boundary signals that assist the listener in parsing the incoming speech stream into words (see, e.g. Cutler and Norris 1988 et seq.). Thus, when there is phrasal disharmony, a shift between harmonic categories of two vowels in sequence will assist listeners by informing them of a greater probability that a word boundary is present. But why vowel harmony should be a simple Markedness effect in Turkish and Finnish, but a *Grenzsignal* in Hungarian, is a mystery to us.

10.2 Learnability

We argued in §9.2 for why, under MaxEnt, we expect that relatively weak phrasal phonological constraints should make their presence felt, albeit subtly. Yet we did not address why such constraints should occur in the grammar in the first place, and how they are related to the word-internal phonology. A plausible mechanism for this comes from Martin's (2011) concept of grammatical "leakage," a form of overgeneralization. His idea is that when children learn the phonotactic restrictions active within words, they weakly overgeneralize, expressing the same constraints in non-word-bounded versions that end up influencing higher-level constructions. He also shows with learning simulations how such overgeneralizations obtain by default under a specific, conservative strategy of language acquisition. If Martinian overgeneralization is correct, it directly follows that the constraint *NÇ̥ (§ 2.7) should generally have yielded no effects in our analyses; it is ineffective within English words and thus cannot be overgeneralized to the phrasal context.

An additional possibility, which seems more radical to us, is that patterns of bigram avoidance are outright learned by children as part of the grammar of their language. This is the obvious explanation to be applied to our Hungarian findings, which remain tentative. The clinching evidence for this (as with Bresnan and Ford's (2010) syntactic work) would be the demonstration of consistent dialect-specific effects in weights assigned to the constraints; and some tentative evidence for this in the case of *SIBILANT CLASH has been offered by Szmrecsanyi et al. (2017).

10.3 Complete grammars

In our study we tried to control for syntactic effects by making a comparison between our Core condition and the Function condition (§8.2), but clearly one could do more: ideally, one would adopt one single probabilistic grammar, along the lines given above, containing a complete set of all the constraints needed for both syntax and phonology. With such a grammar, we could test statistically if the phonological constraints are significantly impacting sentence formation, in a way that could control far more carefully for syntactic effects. Currently, the kind of syntactic grammars that could be adapted to this purpose — by which we mean, computationally-implemented, probabilistic, and comprehensive — are sparse on the ground, but we anticipate that progress on such grammars is likely to be rapid in the future. Such grammars would obviously permit greater rigor in the work that is described here.[21] We also see the pursuit of multi-component grammars as an beneficial counterweight to the increasing separation of subdisciplines in our field, and that such study would help us to share our thinking concerning issues common to both the "S-side" and "P-side" of grammar. [22]

Appendix: Methodology

We defend here our decision to use a MaxEnt grammar as the basis for modeling, as opposed to simpler forms of statistical reasoning.

Our project was originally inspired by Martin's (2011) study of statistical underrepresentation in compounds, which demonstrated that English compounds are formed in lesser numbers when a geminate would be created, as in *bookkeeper*. For some time we actually used Martin's method, which is based on calculating the expected statistics of two-word sequences (for Martin, compounds) if the choice of Word 1 and Word 2 is independent. Martin does this with a "shuffling" procedure: each Word 2 is re-paired with a randomly-chosen Word 1, resulting in a set of shuffled pairs that respects the statistics of the Word 1 and Word 2

[21] For that matter, it could provide greater rigor in dealing with syntactic data: in light of the forcefulness of *IAMBIC CLASH in lowering the probability of a sentence, we think it would be a mistake, for example, to test with consultants a syntactic minimal pair in which only one of the two options included an *IAMBIC CLASH violation.

[22] We can think of: behavior governed by individual lexical items, productivity and exceptionality, diachronic vs. synchronic explanation, the role of listed sequences, free variation, and the relationship of computed probability to well-formedness judgments.

populations. The shuffle is evaluated for violations, then the whole procedure is repeated several thousand times, yielding a probability distribution for violation counts. The counts of the real text are then compared with this distribution, yielding a statistical significance value.

We abandoned this method when we realized that it cannot be trusted to handle cases where constraints apply to overlapping sets of forms, as in our work. To see this, imagine the following language: every word takes the form CVC, where C = one of [p b t d s ʃ z ʒ] and V = one of [i e a o u]. Thus there are 8 × 5 × 8 = 320 possible words — all of which are assumed to exist. We construct a synthetic set of word bigrams by first assembling every possible bigram (320 × 320 = 102,400), then removing precisely one half of the bigrams that contain a *SIBILANT CLASH violation, leaving 89,600 bigrams total. Clearly, the right conclusion to draw for such a text would be that an avoidance of *SIBILANT CLASH is active, and that no other constraint is active in the phrasal domain — the extreme symmetry of the bigram set is meant to guarantee this.

We tested Martin's shuffling method on our imaginary language, with the constraints *SIBILANT CLASH and *GEMINATE. Unsurprisingly, the method found a strong effect of *SIBILANT CLASH (the real count was 0.78 times the expected value from the shuffles, and the effect size was 50 standard deviations). However, the shuffling method also found a strong effect for *GEMINATE (0.82 times expected value, effect size 24 standard deviations) which as noted above is a wrong diagnosis. The reason for the error is that half of the *SIBILANT CLASH violations ([ss, ʃʃ, zz, ʒʒ]) also happen to be *GEMINATE violations.

Analyzing the same language with a MaxEnt grammar gives a very different outcome: *SIBILANT CLASH receives a weight of 0.693, which corresponds (§8.5) to 50% underrepresentation, the correct value. The weight assigned to *GEMINATE is zero, again correct.

Why the difference in performance? The Martinian shuffling procedure has no basis for attributing effects to particular constraints when they overlap in their violation patterns. In contrast, MaxEnt invokes a highly effective procedure intended to predict the data as a whole as accurately as possible; this forces the constraints to do the jobs for which they are best suited — the MaxEnt system (as its name implies) penalizes all empirically unjustified deviations from randomness, in this case, any nonzero weight for *GEMINATE.

In sum, MaxEnt, unlike the shuffling method, is capable of attributing underrepresentation to the appropriate constraint when constraints overlap in coverage, and thus is to be preferred for investigations of the kind we are conducting.

The discussion in this appendix is based on the parallel example given in Wilson and Obdeyn (2009), who address the well-known Observed/Expected statistic (Pierrehumbert 1993) of which Martin's shuffling system is a variant.

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